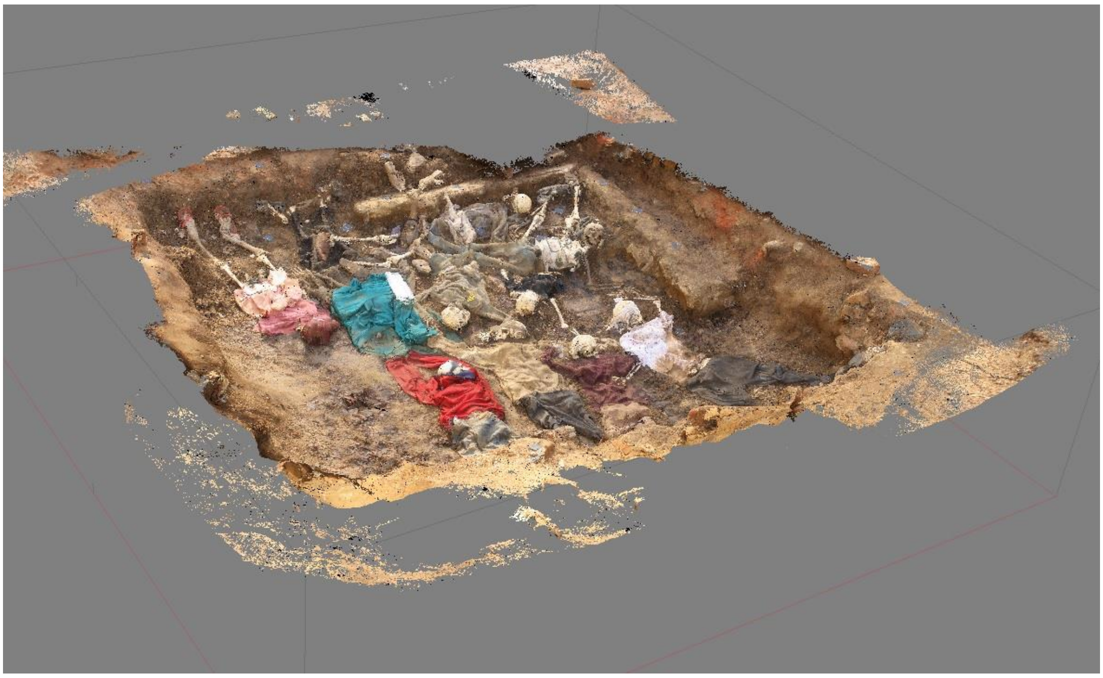
# Digital Close-Range Photogrammetry – A Modern Method to Document Forensic Mass Graves




Anni-Helena Ruotsala
University of Helsinki
Faculty of Arts
Department of Philosophy, History,
Culture and Art Studies
Archaeology

Master's Thesis
2016

| Tiedekunta/Osasto – Fakultet/Sektion – Faculty | Laitos – Institution – Department |
|---|---|
| Humanistinen tiedekunta | Filosofian, historian, kulttuurin ja taiteiden tutkimuksen laitos |

Tekijä – Författare – Author
Ruotsala, Anni-Helena

Työn nimi – Arbetets titel – Title
Digital Close-Range Photogrammetry – A Modern Method to Document Forensic Mass Graves

Oppiaine – Läroämne – Subject
Arkeologia

| Työn laji – Arbetets art – Level | Aika – Datum – Month and year | Sivumäärä– Sidoantal – Number of pages |
|---|---|---|
| pro gradu -tutkielma | huhtikuu 2016 | 64 + 14 liitesivua |

Tiivistelmä – Referat – Abstract

Vaikka nykyaikaisia, konenäön (computer vision) alalla kehitettyjä fotogrammetrisia menetelmiä käytetään yleisesti rikostieteissä, niiden soveltuvuutta joukkohautakaivausten dokumentointiin ei ole arvioitu. Myöskään menetelmien tai niillä tuotetun aineiston hyväksyttävyyttä todisteena oikeudenkäynnissä ei ole määritetty. Fotogrammetria on kuitenkin monilta osin soveltuvampi menetelmä joukkohautojen dokumentointiin rikoskontekstissa kuin nykyisin käytettävä takymetrimittaus: Fotogrammetria on objektiivinen ja kajoamaton menetelmä, jonka avulla todistusaineiston sijainti ja ulkoinen olemus voidaan dokumentoida perusteellisesti ja tarkasti, vaarantamatta todistusaineiston koskemattomuutta (integrity of evidence). Lisäksi fotogrammetria on hyvin nopea kenttädokumentointimenetelmä, ja nykyisten Structure-from-Motion -tekniikoiden avulla kohteista voidaan luoda visuaalisesti tehokkaita, fotorealistisia kolmiulotteisia malleja miltei tai täysin automaattisesti.

Tutkielman tavoitteena on määrittää fotogrammetrian soveltuvuus joukkohautakaivausten dokumentointiin rikoskontekstissa sekä fotogrammetrian ja fotogrammetrisesti tuotetun aineiston hyväksyttävyys todisteena oikeudenkäynnissä. Fotogrammetrian soveltuvuuden määrittämiseksi menetelmää testattiin simulaatiojoukkohautakaivauksella, jossa fotogrammetria ei kuulunut alkuperäiseen dokumentointisuunnitelmaan. Kaivausalueella sijaitsevat maakerrokset ja löydöt valokuvattiin, ja kuvista muodostettiin kolmiulotteiset mallit fotogrammetrisella Structure-from-Motion -tekniikalla. Kenttähavaintoja sekä luotuja pistepilviä ja kolmiulotteisia malleja verrattiin Yhdysvalloissa käytettäviin Daubert- ja Federal Rules of Evidence -standardeihin sekä siihen, miten niitä on sovellettu fotogrammetriaan ja fotogrammetriseen todistusaineistoon. Standardien mukaan oikeudenkäynnissä hyväksyttävän tieteellisen todistusaineiston tulee olla empiirisesti testattavissa, luotettavaa, perustua riittävään aineistoon ja faktoihin, sekä pohjautua luotettaviin tieteellisiin periaatteisiin ja menetelmiin, joita on sovellettu luotettavasti kyseessä olevaan tapaukseen.

Tutkielman perusteella fotogrammetria kykenee, tietyin edellytyksin, täyttämään hyväksyttävälle todistusaineistolle asetetut laatuvaatimukset, ja siten soveltuu hyvin joukkohautojen dokumentointiin rikoskontekstissa. Fotogrammetria soveltuu myös saumattomasti joukkohautakaivausprosessiin, mikäli se sisällytetään kaivauksen dokumentointisuunnitelmaan ja valokuvat otetaan samanaikaisesti rikospaikkavalokuvien kanssa. Käytetyn fotogrammetrisen menetelmän ja sillä tuotetun aineiston hyväksyttävyys todisteena voidaan kuitenkin todentaa vasta, kun tuomioistuin on hyväksynyt tuotetun aineiston todisteeksi oikeudenkäynnissä.

Avainsanat – Nyckelord – Keywords
rikosarkeologia, forensic archaeology, joukkohauta, mass grave, lähifotogrammetria, close-range photogrammetry, Structure-from-Motion

Säilytyspaikka – Förvaringställe – Where deposited
Helsingin yliopisto, keskustakampuksen kirjasto

Muita tietoja – Övriga uppgifter – Additional information

**Acknowledgements**

I would first like to express my sincere gratitude to my advisor Matti Kurkela at Aalto University for his continuous support and interest in my research, and for his valuable comments which incented me to widen my research from relevant perspectives and to deepen my knowledge about photogrammetry. He was always ready to help me whenever I had a problem that I could not solve by myself or I did not know how to proceed with my research.

I would also like to thank my second advisor Mika Lavento, professor of archaeology at the University of Helsinki, and my dear friend Niko Latvakoski for their insightful comments and difficult questions which helped me to keep on track during the writing process. My appreciation also goes to Dr. Anna Williams for her valuable comments, and for the last minute spelling and grammar check.

I am also grateful to Roland Wessling at Cranfield University for the opportunity to conduct my field experiment during the Mass Grave Excavation -module without which it would not been possible to conduct this research. I would also like to thank the Archaeology Department for the possibility to use the necessary software for photogrammetric image processing, and especially Tuovi Laire who organized it. I want to thank Tuovi also for her continuous help during my years of study.

I am also immensely grateful to my husband, my fishing mate, for providing me with his unfailing support and continuous encouragement without which I could not have accomplished my research in otherwise difficult times. Thank you for being by my side for better and for worse. And last, but not least, I am grateful for my two, beautiful children whose smiles keep me going even at hardship.

CONTENTS

# 1 Introduction

## 1.1 Research Rationale

Although scientific excavation of mass graves is a well-established approach in investigating atrocity crimes and numerous published attempts exist (for example, Cox et al. 2008; Haglund et al. 2001 and United Nations 1991), there are no generally accepted standards on how to excavate and document mass graves. However, since most of the mass grave investigators have archaeology backgrounds, the traditional archaeological methods are used. The most established excavation approaches in forensic archaeology include the removal of soil in artificial planes or according to the soil stratigraphy, or the combination of the two (cf., Tuller and Durić 2006). A total station is the most commonly used method to record spatial data in forensic mass grave excavations. The use of laser scanners, on the other hand, is unusual because of the high cost of instruments and required expertise, making laser scanning an as yet non-accessible method in most mass grave excavations. Therefore, laser scanning will not be discussed any further in this thesis.

In both forensic and traditional archaeology, recording relative spatial position of findings is important, because in that way the context of findings can be established and hence, the meaning of findings understood. Since excavation, whether executed for forensic or scientific purposes, is always a destructive process, careful, precise, and complete documentation is necessary: once a site is excavated, the potential research value is limited to the records and recovered evidence. In the forensic context, however, the value of complete and precise records of excavation is emphasized, as the records could be used as evidence in court. Mass graves often relate to atrocity crimes, such as genocides, war crimes, and crimes against humanity, and therefore they have evidential value. In other words, the motivation for investigating mass graves is often to provide evidence for prosecution and thus, only valid methodology that could ensure complete, precise, and high quality evidence recovery should be used.

Although in practice valid methodology and quality requirements for both evidence collection and analysis are defined on a case-by-case basis by the relevant court, the Daubert standard and the Federal Rule of Evidence 702 (later referred as *Rule 702*), used by the federal courts and some state courts in the United States, outline the general requirements for admissible scientific evidence. According to the Daubert standard and Rule 702, admissible scientific evidence should be empirically testable, scientifically falsifiable, reliable and valid, based on sufficient facts or data, and the product of reliable principles and methods, which have also been reliably applied to the facts of the case (*Daubert v. Merrell Dow Pharmaceuticals, Inc.* 1993; Fed. R. Evid. 702).

While a total station is the most commonly used method to record spatial data in forensic mass grave excavations, the admissibility of its data in a court of law must be critically assessed. Using a total station is time-consuming, invasive, subjective in terms of data collection, and very limited in possibilities to present the collected data in court. Therefore, its ability to meet the evidentiary standards (above) is questionable.

In total station surveys, the interpretation of relevant evidence in the field and the time limits for the survey define, in fact, what is being recorded and at which level of detail. Therefore, in case of faulty interpretations, there is a risk that the evidence relevant to the crime was not identified and, consequently, not recorded. Due to the subjective data collection (i.e., because the exact location of points recorded in the field is unknown), and the low possibility of another examiner repeating the exact measurements the admissibility of such evidence could be challenged in legal proceedings. In addition, since total station surveying is very time-consuming, only a rough approximation of an object can be obtained and presented in court. In the forensic context where the purpose of collecting evidence is to provide sufficient factual basis for establishing the criminal responsibility, any method that is biased by subjective data collection, cannot be verified by another examiner, or is unable to ensure the complete collection of evidence, must be replaced with another method.

Nevertheless, for many forensic applications, such as the excavation of single clandestine graves, a total station may well be a sufficient method of recording spatial information, as such features are small in size and fairly simple in their structure. Consequently, the common outputs of total station data, such as stack figures and maps, may also be regarded as a sufficient form of presentation in a court of law. Mass graves, however, are complex in structure and might contain several hundreds of individuals in varied decomposition stages and commingled with each other, which makes the excavation and documentation process, as well as the analysis and presentation of evidence, challenging and time-consuming.

Apart from the internal complexity of mass graves themselves, the forensic context and location bring additional requirements and challenges for evidence collection. There may be attempts to forestall the excavation altogether, by intimidating the forensic experts, misleading the search, or intentionally disguising the location of the mass grave. As extreme measures as reburying the victims elsewhere may be carried out in order to prevent the original burial from being discovered (cf., Skinner et al. 2002). In such conditions, the use of time-consuming documentation methods, such as a total station, could result in loss of evidence and thus, prevent the conviction of the perpetrator(s). In addition, if the mass grave is located in a conflict area, the use of time-consuming documentation methods can also risk the security and health of the investigators.

Because of the above mentioned shortcomings of a total station in the forensic context, there is an obvious need to improve the spatial data collection and analysis in forensic mass grave excavations. Photogrammetry, on the other hand, is a non-invasive, objective, and cost-efficient method that is commonly used in other fields of forensic investigation (see, chapter 1.2.2). By using photogrammetry, both the spatial and visual information of an object is recorded simultaneously and to a high detail, and the acquired images can further (and repeatedly) be processed into an accurate, photorealistic representation of the object to be presented in a court of law.

Moreover, the admissibility of photogrammetry has been established in court (e.g., *Heatherly vs. Alexander* 2005; *Waste Management of Alameda County, Inc. v. East Bay Regional Park District* 2001; *Napeahi vs. Wilson* 1996; *United States v. Quinn* 1994; *Goodman vs. Crystal River* 1987; *Missouri vs. Department of Army Corp. of Engineers* 1980; *Canal Authority of Florida v. Callaway* 1974). Its applicability to forensic mass grave excavation, however, has not been assessed. Therefore, in this thesis, its feasibility for documenting forensic mass graves, and for analyzing and presenting the collected evidence is evaluated according to the requirements outlined in the Daubert standard and Rule 702, listed earlier.

Evidentiary requirements, outlined in Daubert and Rule 702, however, set additional requirements for photogrammetric field procedure, image processing software and data management, which have to be taken into account when applying photogrammetry in a forensic mass grave excavation. These aspects will further be discussed in chapters 4.3 *Photogrammetry and Evidentiary Requirements* and 5 *Conclusions.*

## 1.2 Theoretical Framework

Photogrammetry as a science is as old as photography itself (for the history of photogrammetry, see, Konecny 1996), but it was not until after the emergence of digital image acquisition sensors, the improvements in storage and computing power of computers, and the developments in image processing techniques when its exploitation expanded to other disciplines as well. As the result, a vast number of applications (for example, archaeology) and publications exist, reviewing of which for the purposes of this thesis, given the forensic context of it, would be both unpractical and unnecessary. Hence, only the relevant research literature regarding the use of close-range photogrammetry in the forensic context and forensic mass grave excavations is introduced in this thesis.

Photogrammetry is a well-established method in forensic science, and thus there are a great number of forensic applications of photogrammetry and established standards for ensuring the admissibility of evidence in the forensic context (see, for example, Forensic Science Regulator 2014; Scientific Working Group on Digital Evidence 2015). Photogrammetry, as defined by the American Society for Photogrammetry and Remote Sensing, is “the art, science, and technology of obtaining reliable information about physical objects and the environment, through processes of recording, measuring, and interpreting images and patterns of electromagnetic radiant energy and other phenomena”. Although the term *photogrammetry* refers to a wide variety of both imaging (e.g., aerial photography, stereo-photogrammetry, X-ray-photogrammetry, etc.) and image analysis techniques (e.g., analytical and digital photogrammetry), only the digital close-range (also known as *terrestrial*) photogrammetry is discussed in this thesis. Digital close-range photogrammetry (later referred as *photogrammetry*) refers to a combination of techniques where the camera is close to the object and the images are both acquired and analyzed digitally.

### 1.2.1 Fundamentals of Photogrammetry

Photogrammetry is based on the geometrical relationship between a 3D point of an object and its corresponding 2D point in an image. Due to the image formation process where the bundle of light reflecting from the object is recorded as a projection into a 2D plane in the camera sensor (Fussell 1982: 157), the 3D geometry of an object can be reconstructed from 2D images. According to the principle of collinearity, the projection center, a point in the image, and the same point in the target are located on the same line (Brown 1971 and 1976;
Figure **1**). Each point in an image can therefore be returned into the original 3D location of the object, and vice versa.

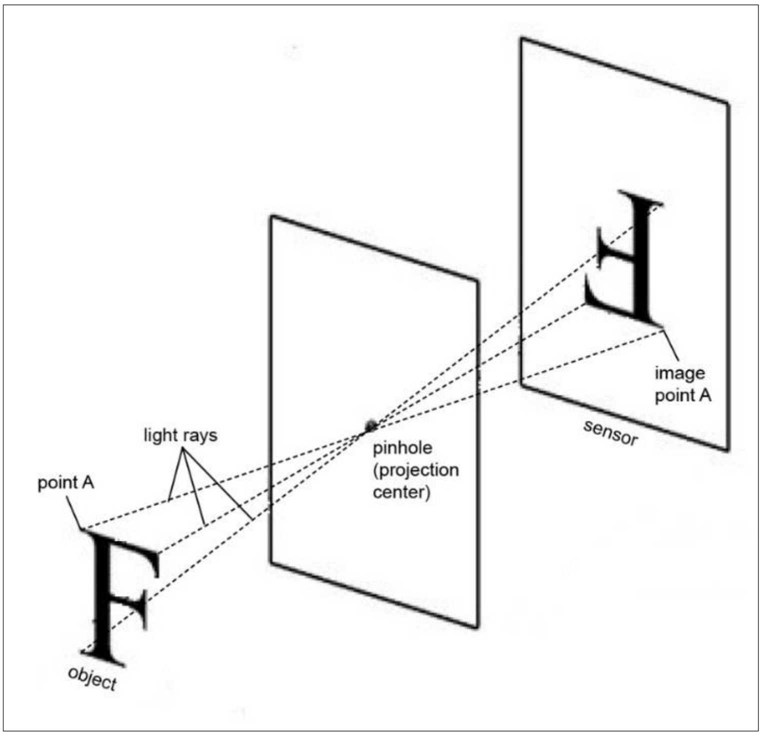



***Figure 1.*** *Geometry of a pinhole camera (modified from: http://www.northlight-images.co.uk/article_pages/Canon_1ds_pinhole.html). The pinhole camera model ignores geometric (or any other) distortions caused by camera lenses and should therefore be regarded only as a theoretical model and mathematical estimation tool. In practice, distortions should always be estimated and minimized, so that the principal of collinearity is realized and reliable interpretations can be derived.*

The reconstruction of a 3D object from images requires reconstructing the bundle of light that was cut by the image plane. This process demands knowledge about the camera geometry. In the internal orientation, the location of the principal point, the focal length value (the camera constant), and the camera distortions are defined (see, Brown 1966 and 1971). In practice, the internal orientation is solved in camera calibration. Camera calibration can be performed either separately, or as a part of image processing (*auto-calibration*), such as in the Structure-from-Motion approach – if high accuracy results are required, separate calibration is recommended. In applications of high metric accuracy[1], such as topographical

[1] *Accuracy* refers to the measure for estimating how well the reconstructed 3D point in, for instance, point cloud or 3D model represents the true location of the same point in the original object. Often accuracy is estimated by comparing photogrammetric results with, e.g., laser scanning data. Accuracy of photogrammetric measurements depends on, e.g., the resolution of the

surveys, image locations are usually transformed into a real world coordinate system (i.e., georeferencing). However, in forensic mass grave excavations high relative accuracy (i.e., precision[2]) is often more important than high metric accuracy (Figure 2), therefore knowing the scale of the images (i.e., a distance in an image the ground distance of which is known) and the generated outputs is often all that is required. In (forensic) archaeology, it is the relative location and context of evidence rather than their accurate spatial location that is required to derive most of the meaning from a mass grave site. If accurate spatial location of evidence is, however, required for further analysis of evidence, then images must also be georeferenced using geodetically (e.g., a total station) measured tie points (i.e., easily recognizable features on the ground that are visible in the images).

### 1.2.2 Forensic Applications of Photogrammetry

In the forensic context, the advantages of photogrammetry are well-recognized, and thus the method is commonly used, for instance, for documenting crime scenes, recording and reconstructing traffic accidents (e.g., Arnold et al. 2008; Fraser et al. 2008), and for estimating the height of an offender from CCTV material (e.g., Epure 2012; Lynnerup et al. 2007). Photogrammetry is also used in forensic medicine, for example, for bite mark documentation and analysis (e.g., Thali et al. 2003), skin imprint mark analysis (e.g., Robertson 2000), forensic-related injury analysis (e.g., Thali et al. 2000), and forensic postmortem investigations (e.g., Urbanova et al. 2015). Photogrammetry has also been used in fire investigations (e.g., King and Ebert 2002).

camera, the number of images, image quality, the measurement accuracy of the control points, and the quality of camera calibration.

[2] *Precision* (repeatability) refers to the measure for estimating how consistent or close to each other different measurements are, or how well two separate, for instance, point clouds of the same object obtained with the same method are comparable with each other. Precision is often assessed by repeating measurements to achieve measurement error.

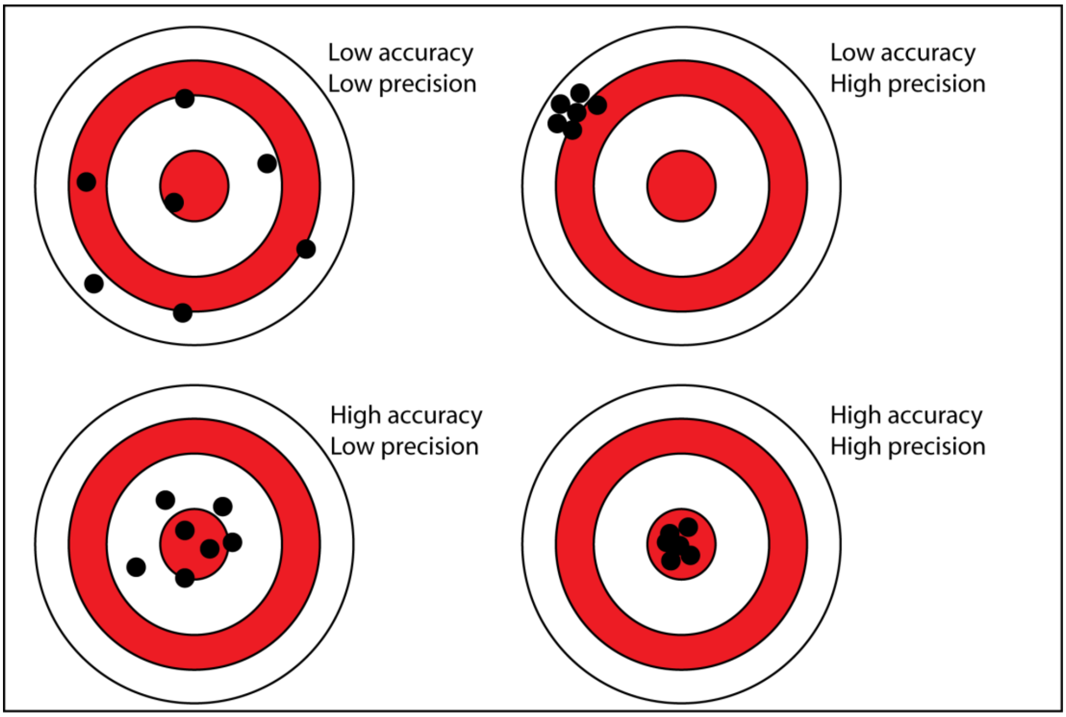



***Figure 2***. *Precision versus accuracy. The bullseye represents the true value, e.g., the true location of the object, while black dots represent measurements, e.g., the estimated 3D locations of the object based on the 2D images. Source: http://www.antarcticglaciers.org/glacial-geology/dating-glacial-sediments-2/precision-and-accuracy-glacial-geology/. Accessed 7.4.2016.*

Regardless the established use of photogrammetry in forensic science, there have only been a few attempts to apply the method to mass grave excavations. Ducke et al. (2011) outline an approach of using Structure-from-Motion (SfM), successively used, for instance, in archaeology for recording excavations (e.g., De Reu et al. 2014; Howland et al. 2014; Alby et al. 2013; De Reu et al. 2013; Forte et al. 2012; Callieri et al. 2011), and open source software to reconstruct the 3D structure of a mass grave from existing photographs. Seitsonen and Holappa (2011) provide a useful, although very cursory, comparison of the field performance of field sketching, total station surveying, laser scanning and photogrammetry in a mass grave site. Photogrammetry was also used for documenting a mass grave in Beacon Island, Houtman Abrolhos Islands, Western Australia (Paterson and Franklin 2004: 73, 74), but no in-depth description of the used techniques is provided. None of the above mentioned cases, however, concerns the documentation of a forensic mass grave, and therefore many of the issues related to the forensic context and the requirements for admissible evidence collection remain unaddressed.

Also the more recent study by Baier and Rando (2016) on using Structure-from-Motion and the PhotoScan software (by Agisoft) in mass grave documentation fails to address the above mentioned issues. Instead, its input to the research field is in providing an insight into the advantages and disadvantages of the Structure-from-Motion approach compared to those of laser scanning and total station surveying, and in describing the general workflow of the approach using PhotoScan software.

Regardless the increasing number of applications and research literature on the use of photogrammetry in the forensic context, very little has been written about its admissibility in court.

## 1.3 Aims and Objectives

The aim of this thesis is to determine the applicability of photogrammetry to forensic mass grave excavations and the forensic context in general. To investigate the applicability of photogrammetry to forensic mass grave excavation, the method is tested in practice by applying the Structure-from-Motion method to a simulated mass grave excavation where photogrammetry was not a part of the documentation strategy. By doing so, the practicability and potential of photogrammetry in forensic mass grave excavation can be strutinised and critically assessed. Furthermore, photogrammetry and the generated outputs of the simulated mass grave are evaluated according to the requirements of the Daubert standard and Rule 702 of the Federal Rules of Evidence for admissible scientific evidence (see chapter 1.1) and the way courts have applied them to photogrammetric evidence, to establish the admissibility and hence, the applicability of photogrammetry to the forensic context.

Even though some comparisons between photogrammetry and a total station, the most commonly used method of recording spatial data in mass grave excavations, are made to highlight the advantages and limitations of photogrammetry, this thesis is not a technical comparison of accuracy or resolution or any other technical aspects of these two methods (the reader is instead referred to e.g., Remondino et al. 2014; Doneus et al. 2011).

# 2 Simulated Mass Grave Excavation

To determine the applicability of photogrammetry to forensic mass grave excavation, the method was tested in practice in a simulated mass grave excavation that had been organized as a part of the Mass Grave Excavation module of the Forensic Archaeology Masters Programme at Cranfield University.

Due to the context of the excavation, photogrammetry was not a part of the pre-defined documentation strategy in the simulated mass grave excavation. Permission from the excavation manager to use photogrammetry in the excavation was, however, obtained on one condition: the use of photogrammetry must not disrupt or in any way affect the pre-defined excavation process and schedule. As the result, instead of adjusting the documentation strategy so that the requirements for successful photogrammetric documentation could be met, photogrammetric approach had to be adjusted to the strategy and schedule of the excavation. This had a significant impact on the photogrammetric field procedure and, consequently, on the image quality.

## 2.1 Simulated Mass Grave

The simulated mass grave, with a size of 3,94 m long by 3,57 m wide by 0,3 – 0,74 m deep, had been built on the premises of Cranfield University, Shrivenham, England. The mass grave was excavated and documented according to the common practice in forensic mass grave excavations, i.e., in informal planes and documented using a total station, photography, a set of recording forms and making field notes. The mass grave concealed twelve anatomically correct plastic teaching skeletons, some of which were lying parallel to each other and some commingled.

## 2.2 Photogrammetric Method

Initially, the conventional photogrammetric approach, being the state-of-the-art method at the time, was selected for image acquisition and processing (see targets in the images). Since then, however, there have been major developments in the image based (computer vision) algorithms, previously known to be very sensitive to errors in image measurement (Oliensis 2000; Tomasi & Zhang 1995), in terms of measurement accuracy and level of automatisation (Shan et al. 2013; Furukawa et al. 2010; Pollefeys et al. 2008; Snavely et al. 2008; Goesele et al. 2007; Hartley and Zisserman 2003). As the result, they have superseded the conventional photogrammetric techniques and, hence, represent the-state-of-the-art method today (see also, Fraser 2015; Fonstad et al. 2013; James and Robson 2012). Therefore, the Structure-from-motion (SfM) method, combining the theory of photogrammetry and the algorithms developed in computer science, was used in the field experiment instead.

Structure-from-Motion refers to a method where the 3D structure of an object is estimated based on the motion of the object (or the relative 3D motion between the camera and the scene) (for the mathematical basis, see, e.g., Hartley and Zisserman 2000). In Structure-from-Motion, the scene geometry and camera parameters (both internal and external) are solved automatically from overlapping photographs by using an iterative bundle adjustment procedure: In the Structure-from-Motion method, common feature points between the images are identified automatically, most commonly using a scale invariant feature transform (SIFT) algorithm (Lowe 1999), and matched using bundle adjustment to establish the internal and external orientation parameters (i.e., camera calibration). For this process to be successful, some distinct features in the scene that are also visible in the images are required, as this approach performs poorly with transparent, reflective, or homogenous surfaces (Micheletti et al. 2014). Ground, whether excavated or not, is therefore an ideal scene for this method, as it is usually a heterogeneous and non-reflective surface with numerous distinct features, such as rocks. For further reading about SfM method and its limitations, see, Remondino et al. 2014; Remondino et al. 2012; Szeliski 2010; Fisher et al. 2005; Hartley and Zisserman 2004; Ullman 1979. For comparison with the conventional photogrammetry, see, Schrotter (2009: 45-52).

### 2.2.1 Photogrammetric Image Acquisition

The following procedure was followed during the image acquisition to ensure successful image processing (i.e., automatic feature extraction and matching, and camera calibration) (cf., Micheletti et al.2015):

The mass grave was photographed from different angles and distances (i.e., convergent imaging geometry) using a Canon EOS 450D single-lens reflex (SRL) camera. A systematic pattern around the grave was followed, taking images every 50 cm at full standing height from two different distances (standing at the edge of the grave and 1 meter further from the edge) to ensure sufficient overlap between the images (i.e., the same point would be visible in at least three different images; see, Figure 3) and coverage of the grave. In addition, the plastic skeletons were photographed from a closer distance. This approach is known to improve the measurement accuracy, and enabled the maximum overlap between the images and flexible data acquisition as images could be taken by walking around the simulated mass grave. Due to the flexible data acquisition, the full coverage of the grave could be ensured. Another advantage of the convergent image acquisition geometry was the reduced image number due to the great overlap between the images.

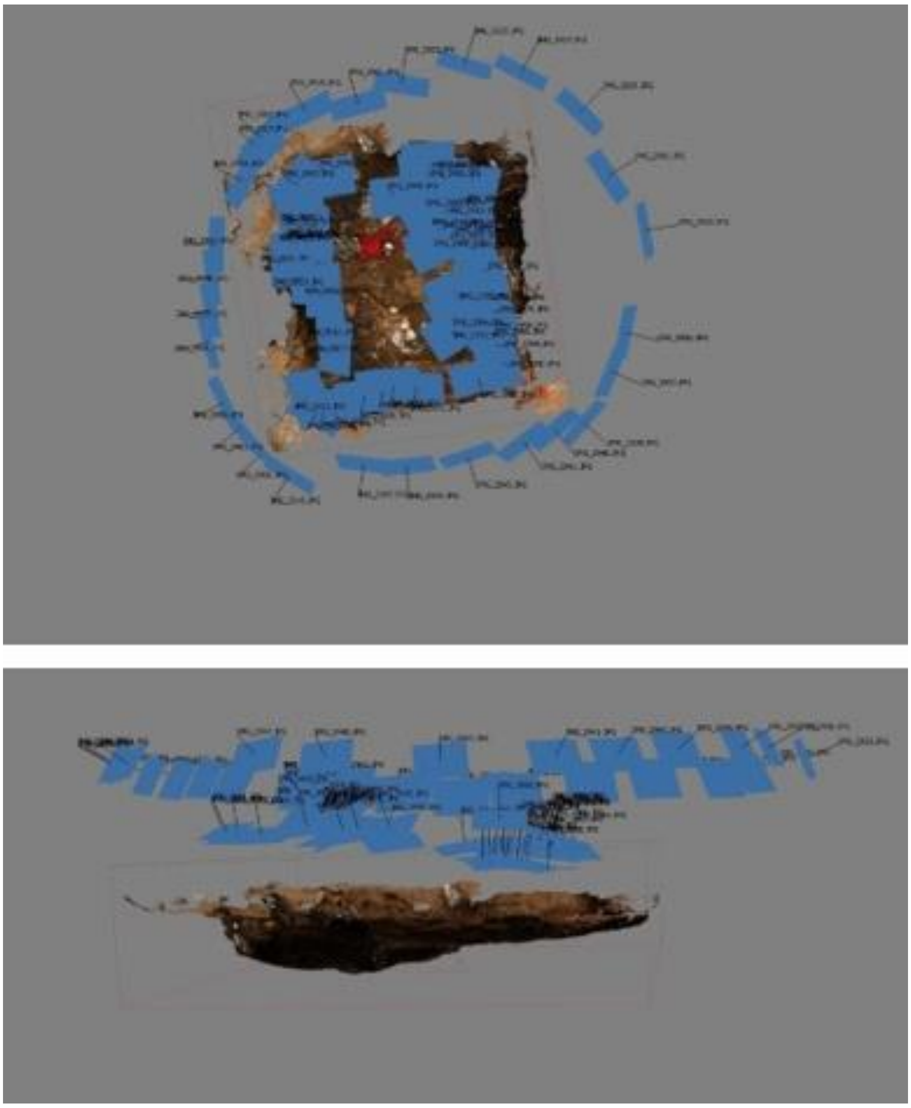


***Figure 3***. *The camera positions (blue rectangles), as seen in PhotoScan. The upper image shows the image acquisition geometry from above, while the lower image shows different heights in side view*.

In total, 1082 images were taken to ensure the full coverage of the grave in the images and a sufficient number of high quality images for 3D model generation. Depending on the layer, 44-80 images were used as input for image processing to produce more reliable point clouds and denser meshes, and to improve model accuracy (Micheletti et al. 2014).

Since a fixed focal length (or fixed focus) lens was not available for the field test, an 18-55 mm consumer grade zoom lens objective at the minimum focal length (18 mm) was first focused to 5 meters, to ensure that the majority of the grave would be in focus in the images, and then taped as a precaution for minimising inaccuracies in camera calibration (i.e., interior orientation) (cf., Shortis et al. 2006). The flash was also avoided in the documentation of most layers, so that the feature matching process would not be confused with inconsistent image textures (Micheletti et al. 2014). This, however, was not possible at all times, because images could only be taken whenever it was possible, and therefore no control over lighting conditions during image acquisition could be exercised. As the result, the flash had to be occasionally used to compensate the decreasing daylight, because no additional light sources, such as spot lights, were available. Similarly, due to the given time limits for photogrammetric image acquisition, it was not possible to block out or shadow direct sunlight. Although feature matching process was successful despite the varying lighting conditions, they caused significant brightness differences between images and image subsets, which were also visible in the generated 3D models.

### 2.2.2 Photogrammetric Image Processing

*Software*

For the 3D reconstruction, a SfM based, commercial software called PhotoScan (professional edition, version 1.1.6) (run on a desktop PC outfitted with a 3.2 GHz Intel Core i5-4570 processor, 16 GB of RAM, and Intel HD Graphics 4600 GPU) by Agisoft LCC was used, and the standard workflow of the software for 3D reconstruction (Agisoft LCC 2014) was followed. With this software, the 3D reconstruction is performed in four steps: (1) image alignment and sparse point cloud generation, (2) dense point cloud generation, (3) dense 3D surface generation (mesh), and (4) texture mapping.

The software was chosen because of its high performance and the high level of automatisation in image processing. Furthermore, the software is also commonly applied in, for instance, archaeology (e.g., Forte 2014; Barsanti et al. 2013; Forte et al. 2012; Plets et al. 2012; Doneus et al. 2011, etc.) and forensic science (e.g., Leipner et al. 2016; Urbanova et al. 2015, etc.). A combination of parameters ensuring the best quality 3D models of the grave with a reasonable computing time was used for 3D reconstruction (Appendix 1).

### *Preparations for 3D Model Generation*

Images were first divided into subsets (*chunks* in PhotoScan), each subset representing each exposed excavation layer (Table 1; Appendix 1), and then processed separately. This approach was applied so that the excavation layers, or the 3D models of them, could be analysed individually in the software, as otherwise another software (see, Baier and Rando 2016) would have been required. Images included in each subset were selected based on their visual appearance and image quality, determined by the automatic image quality estimation feature of PhotoScan software. Images with poor lighting, taken with a flash, and unsharp images (images with the quality value less than 0.5 units) were excluded from further image processing.

***Table 1***. *Images of the simulated mass grave were divided into subsets according to the excavation layers.*

| **Layer** | **Description** | **Images in total** | **Images used as input** |
|---|---|---|---|
| L0 | Ground disturbance consistent with a grave | 51 | 44 |
| L1 | Topsoil removed, but grave cut not well defined | 196 | 65 |
| L2 | Grave cut defined and the surroundings of the cut cleared | 83 | 80 |
| L3 | First pieces of evidence exposed | 126 | 76 |
| L4 | First individuals exposed | 186 | 77 |
| L5 | Ten individuals exposed | 240 | 80 |
| L6 | Six individuals recovered and four remaining ones exposed | 132 | 75 |
| L7 | Empty grave | 68 | 57 |
| In total | | 1082 | 554 |

This approach, however, could not been applied to all the image subsets, as both the number of images per layer (see, Table 1) and the quality of acquired images varied significantly (Appendix 1) depending on how much time there was for documentation, the level of detail in the exposed layer, and on the excavation phase at the time of image acquisition. For example, the layer 4 had to be photographed during an ongoing excavation, and thus the field staff and tools could not be excluded from the scene before taking the images (Figure 4). Layer 1 (Figure 5), on the other hand, had to be photographed after the working hours, in rapidly decreasing day light, which caused extreme brightness differences between the images and required that the flash had to be used in occasion.

***Figure 4****. Some of the layers had to be photographed as they were being excavated. Layer 4.*

***Figure 5****. Some of the layers had to be photographed in decreasing day light. Layer 1.*

*Workflow of 3D Model Generation*

The results of image processing, as well as the software settings used in each processing phase, can be found in Appendix 1.

*(1) Image Alignment and Sparse Point Cloud Generation*

The reconstruction of a 3D object from photographs requires knowledge about the camera geometry. In the internal orientation, the location of the principal point, the focal length value (the camera constant), and the camera distortions are defined (i.e., camera calibration). In the Structure-from-Motion method, both internal and external orientation parameters are established automatically; if high accuracy 3D reconstruction results are required, the camera should be calibrated separately using targets or chessboards, and only the external orientation established using automatic techniques. In PhotoScan software, used in this experiment, a number of common features between images are identified and matched automatically during image alignment to establish the internal and external orientation parameters, including nonlinear radial distortions (according to AgiSoft LCC 2014, Brown's distortion model (Brown 1966) is applied), using image data alone. During adjustment, the reconstructed scene data, including the model geometry and camera positions, is transformed so that the RMS error between estimated and measured camera positions is minimized (i.e., least square adjustment). In PhotoScan software, the camera parameters (camera model and type, sensor size, image resolution, focal length, aperture, ISO value, shutter speed, and principal point coordinates) are estimated for each image. As the result, a sparse point cloud and a set of camera positions are formed (Figure 6) and error estimates for alignment (effective overlap and reprojection error[3]) computed (see, Appendix 2). (AgiSoft LCC 2014.)

[3] According to AgiSoft LCC 2014: 45, "[h]igh reprojection error usually indicates poor localization accuracy of the corresponding point projections at the point matching step. It is also typical for false matches."

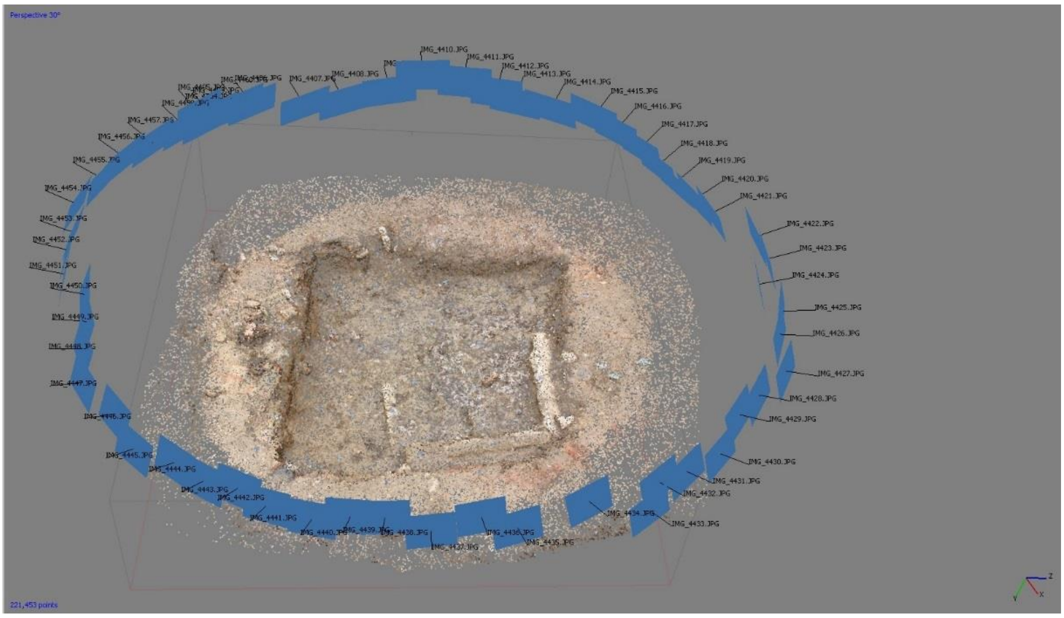
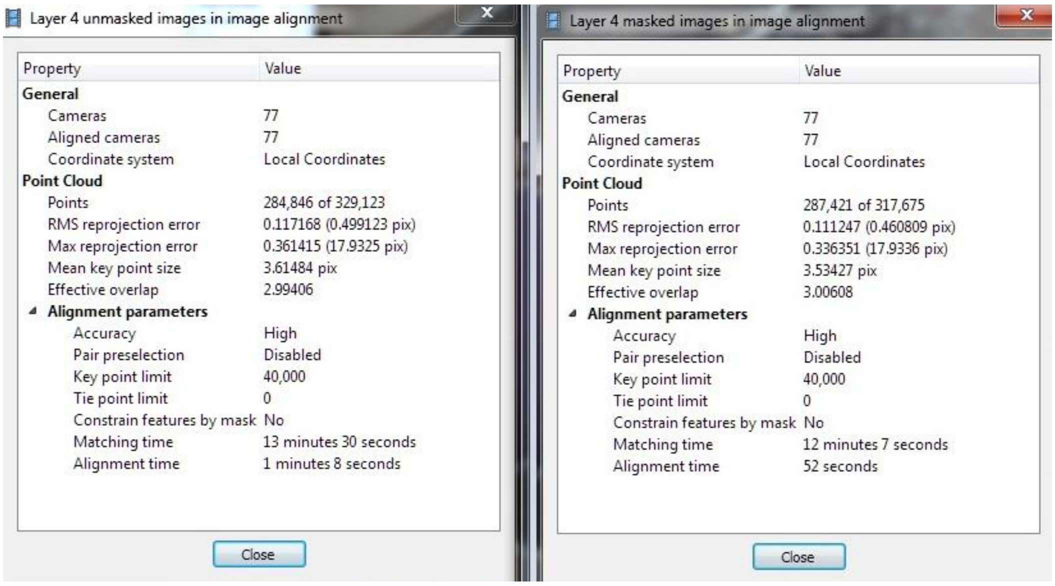


***Figure 6****. The sparse point cloud and camera positions for Layer 7, as seen in PhotoScan.*

Image alignment is one of the most rapid phases of 3D reconstruction, and thus a high number of images is recommended to be used as input to produce more reliable point clouds and denser meshes, and to improve model accuracy (Micheletti et al. 2014). In many cases, however, the time contraints for post-processing, and computer performance might require smaller image sets to be used. For example, when tested, the alignment of 111 images of layer 4 (settings: high accuracy and pair preselection disabled) took approximately 29 minutes, while generating a dense point cloud increased the processing time to 9,5 hours (cf., Appendix 1; see also, Baier and Rando 2016; Fonstad et al. 2013; James and Robson 2012; Westoby et al. 2012). Consequently, the number of images in a subset, representing an excavation layer, was reduced to 44-80 images to spare computer memory, keep processing times reasonable, and, yet, to ensure high quality 3D models (see, Appendix 1).

The problems during the image acquisition became evident during image alignment. Due to the image acquisition conditions during the excavation, described earlier, the field staff and tools could not be removed from the scene before taking the images of Layers 4, 5, and 6. Hence, in some images, the field staff and tools block the view of the simulated mass grave. PhotoScan software provides a masking tool with which areas and objects that are not of interest can be excluded from image alignment process so that they would not confuse the estimation of camera positions (AgiSoft LCC 2014). As the result, the images of Layers 4 and 5 were masked with the masking tool of PhotoScan (Figure 7), and the masks applied in image alignment to achieve more accurate camera positions. Masking increased the number of the matched tie points between the images and the effective overlap, and decreased the reprojection error (Figure 8) and the number of points representing tools and the field staff (Figure 9).

***Figure 7.*** *Masked image of Layer 4, as seen in PhotoScan. Masked areas in the image (grey areas) were excluded from image alignment process.*



Layer 4 unmasked images in image alignment

| Property | Value |
|---|---|
| **General** | |
| Cameras | 77 |
| Aligned cameras | 77 |
| Coordinate system | Local Coordinates |
| **Point Cloud** | |
| Points | 284,846 of 329,123 |
| RMS reprojection error | 0.117168 (0.499123 pix) |
| Max reprojection error | 0.361415 (17.9325 pix) |
| Mean key point size | 3.61484 pix |
| Effective overlap | 2.99406 |
| **Alignment parameters** | |
| Accuracy | High |
| Pair preselection | Disabled |
| Key point limit | 40,000 |
| Tie point limit | 0 |
| Constrain features by mask | No |
| Matching time | 13 minutes 30 seconds |
| Alignment time | 1 minutes 8 seconds |

Close

Layer 4 masked images in image alignment

| Property | Value |
|---|---|
| **General** | |
| Cameras | 77 |
| Aligned cameras | 77 |
| Coordinate system | Local Coordinates |
| **Point Cloud** | |
| Points | 287,421 of 317,675 |
| RMS reprojection error | 0.111247 (0.460809 pix) |
| Max reprojection error | 0.336351 (17.9336 pix) |
| Mean key point size | 3.53427 pix |
| Effective overlap | 3.00608 |
| **Alignment parameters** | |
| Accuracy | High |
| Pair preselection | Disabled |
| Key point limit | 40,000 |
| Tie point limit | 0 |
| Constrain features by mask | No |
| Matching time | 12 minutes 7 seconds |
| Alignment time | 52 seconds |

Close

***Figure 8.*** *The results of image alignment with unmasked images (left) and the masked images (right). Applying masks in image alignment of Layer 4 improved the image alignment results.*

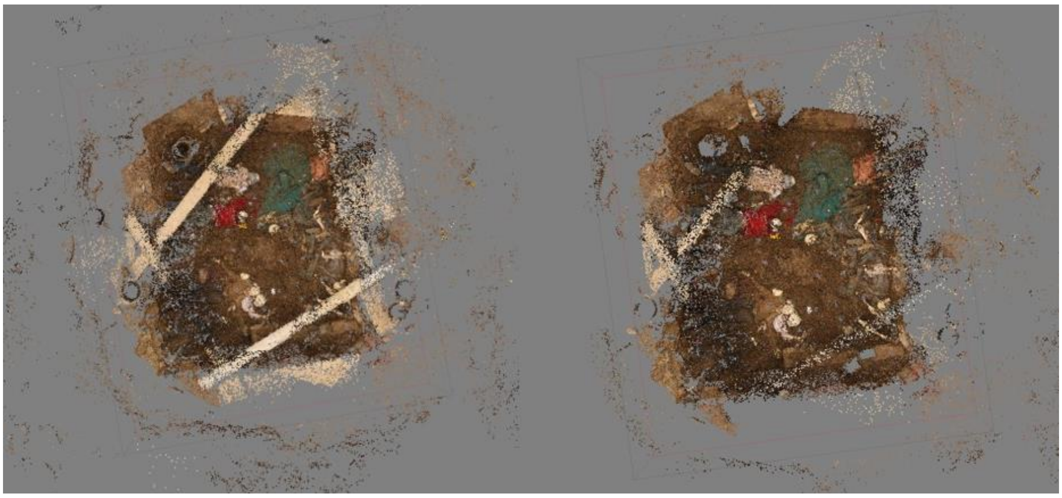


***Figure 9****. Sparse point cloud of Layer 4, generated from unmasked (left) and the masked (right) images. Masking decreased the number of points representing the field staff and tools that were blocking the view of the simulated mass grave, but could not, however, exclude them altogether.*

Masking, however, did not prevent masked areas from appearing to the generated sparse point cloud (Figure 9), or to the dense point cloud (Figure 10) (cf., Agisoft LCC 2014: 41-42). Instead, they had to be removed manually from the dense point cloud to exclude them from mesh (i.e., 3D model) generation. Because masking of images was very time-consuming and not necessary for answering the research questions of this thesis, it was not performed on other layers.

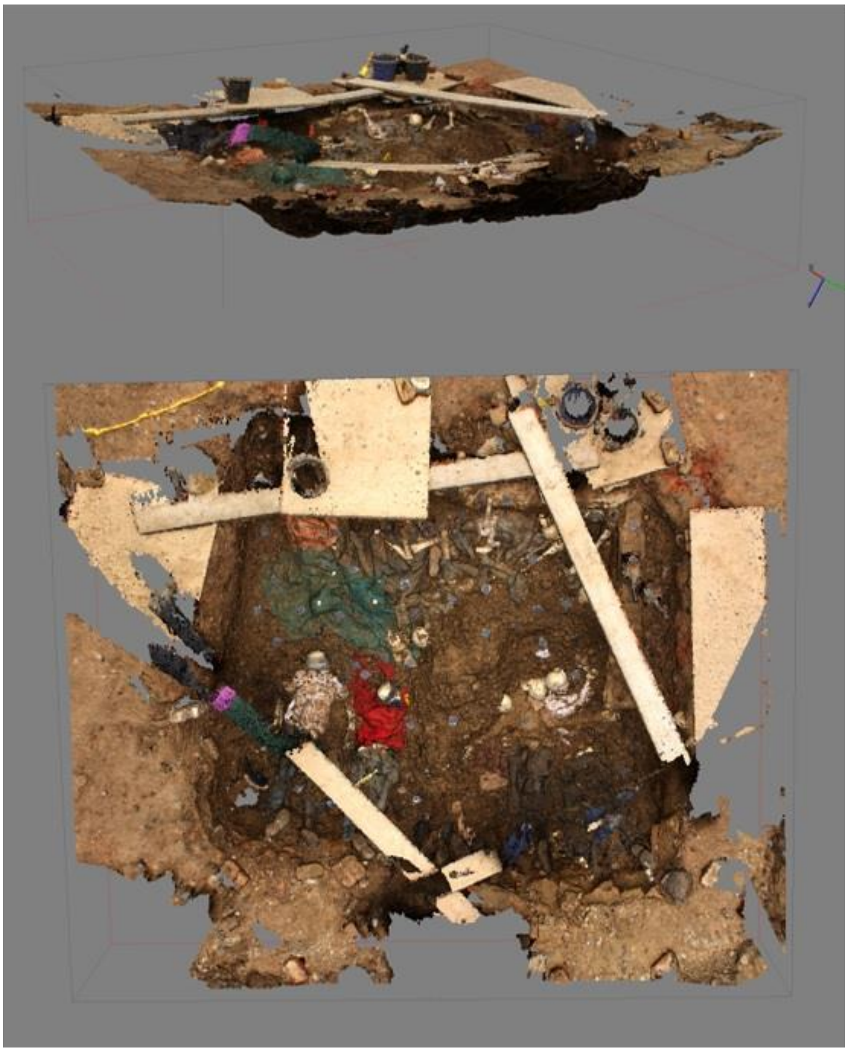


***Figure 10***. *Dense point cloud of Layer 4, generated from the masked images. In spite of masking images, the field staff and tools appeared to the dense point cloud of Layer 4.*

*(2) Dense Point Cloud Generation*

In this step, a dense cloud of 3D points representing the object is computed based on the images and the estimated camera positions, using dense stereo matching and pair-wise depth map computation (Verhoeven et al. 2012: 2064). In dense point cloud generation, depth information for each camera is calculated and combined into a single dense point cloud (Agisoft LLC 2014). As dense point cloud generation is based on the individual pixel values (*ibid.*), this step is the most time-consuming phase of 3D model generation (processing time depends on image resolution and number of images) (Appendix 1).

Using masked images of Layer 4 as input for dense point cloud generation did not prevent points representing the field staff and tools from appearing to the generated dense point cloud. Therefore, they had to be removed manually from the dense point cloud to exclude them from mesh (i.e. 3D model) generation, which resulted in gaps in the point cloud (Figure 11) and the subsequent 3D model. Although PhotoScan software provides a tool to close gaps in a 3D model, it was not used due to the evidentiary requirement of authenticity (Fed. R. Evid. 901).


***Figure 11***. *Dense point cloud of Layer 4 after manual editing. Removal of points representing the field staff and tools resulted in gaps in the dense point cloud.*

*(3) Dense 3D Surface Generation (Mesh), and (4) Texture mapping*

In this step, the 3D points of a dense point cloud are connected to form a network of triangles, a polygonal model (a mesh in PhotoScan) approximating the shape of the object (AgiSoft LCC 2014). In this step, a pair-wise binocular stereo approach (Bradley et al. 2008) is applied to compute estimate of the distance between the camera and the object surface (i.e. depth map) for almost every pixel of each image, and then merged into a single 3D model (Verhoeven et al. 2012). The generated 3D model can be further texturised to obtain a photorealistic visualisation of the object (see, Appendix 1).

Due to the context of this thesis, the 3D model was not georeferenced nor scaled; the 3D visualisation and the relative spatial record of the simulated mass grave were sufficient to answer the research questions of this thesis (see also, chapter 1.2.1).

# 3 Performance of Photogrammetry in the Simulated Mass Grave Excavation

## 3.1 Photogrammetry in the Field

As mentioned earlier, the simulated mass grave excavation was not conducted for the purposes of this thesis, but as a part of the Forensic Archaeology Masters Programme at Cranfield University. Therefore, photogrammetry had not been included in the pre-planned documentation strategy, but on the contrary, had to be adjusted to the existing strategy and schedule. Consequently, images for photogrammetric processing could not be taken in the ideal manner for 3D model generation, but without preparing the scene for photography (including the measures for preventing over- and underexposure of the images), and only from the layers exposed at the time of photography. Some exposed layers also had to be photographed in decreasing daylight, without additional light sources available and hence, a flash had to be used in occasion. (See, Appendix 1.)

For successful photogrammetric documentation of the excavation process that enables the later assessment of the excavation strategy and validation of the derived interpretations, each layer, once exposed, should be photographed in situ before the recovery of evidence. In the field experiment of this thesis, however, this was not possible, since only the layers exposed during photography could be recorded. As the result, one plastic skeleton was recovered before it could be documented for this thesis. Therefore, the acquired images do not fully reflect the excavation process and all the evidence recovered during the simulated mass grave excavation.

Furthermore, in ideal situation, images for photogrammetric processing would be taken simultanously with scene photographs, as in that way the scene could be prepared for both types of photography without extra effort. In excavations, whether forensic or archaeological, the common practice is to prepare the scene for photography by, for instance, cleaning the exposed layer from loose dirt; removing extra objects, such as tools or field staff, from the scene; ensuring consistent light conditions; and by adding a scale and a north arrow, to ensure high quality images. In this case, however, the scene could not be prepared for image acquisition nor could photogrammetry be applied during scene photography, which decreased the quality of the images and further data outputs, as described in chapter 2.2. In photogrammetry, image quality has a central role, as it affects directly the quality of the derived outputs, such as a 3D model.

Since no modifications to the documentation strategy could be made so that the requirements of photogrammetry could have been met, photogrammetry did not fit seamlessly to the excavation process, and additional effort was required in image processing to improve the quality of the photogrammetric outputs (see, chapter 2.2).

## 3.2 Advantages of Photogrammetry

Based on the field experiment, photogrammetry was found to have significant advantages in the forensic context over a total station, the most commonly used documentation method in forensic mass grave excavations.

First, unlike a total station, photogrammetry requires no contact with evidence during the documentation and hence, there is no risk of destroying evidence or its context, or changing the in situ location of evidence by accident. Since no contact with evidence is required, the integrity of evidence can be preserved during the documentation. In the forensic context, the integrity of evidence is vital, as if in doubt, its use in legal proceedings could be jeopardized, possibly preventing the conviction of perpetrator(s). Therefore, merely the non-invasive nature of photogrammetric documentation advocates its use in the forensic context over a total station.

Second, the photogrammetric record of the simulated mass grave is outstandingly richer and more complete than the one obtained with a total station (Figure 12): while only the points selected by the operator are recorded with a total station, with photogrammetry *everything* visible for the camera is recorded as *infinite* number of points. For example, in the field experiment, even the tiniest details, such as tire marks, were visible already in the generated dense point clouds due to the high point density of the clouds (see, dense point cloud of Layer 0 in Appendix 1). This is an important advantage in the forensic context where collection of sufficient data is required for providing reliable factual basis for the prosecution and decision making process (cf., Fed. R. Evid. 702b). While the total station record of the simulated mass grave excavation consisted of 635 points in total, 156 points of which represented all the 12 skeletons, the dense point cloud generated from (57) images of a single excavation layer (layer 7) included at least 4,890,287 points (when high quality settings were used), and with significantly less field-effort.

Moreover, photogrammetry not only enables the 3D reconstruction of an object with its 3D location, but also provides visual information about the object, enabling the generation of a photorealistic 3D representation of the object (see, Appendix 1) that can be rotated and zoomed. Photorealistic visualizations can further be used for representing the circumstances in the field and the evidence in its context, for establishing the sequence of excavation process, (see, Appendix 1), and for the validation of interpretations and the methodology used in evidence recovery.

Furthermore, images for photogrammetric processing are nowadays taken in digital format, which makes the method very time-efficient, as various outputs (e.g. orthophotos, plans, sections, digital elevation and surface models) can be generated semi- or fully automatically. In photogrammetry (and computer vision), the possibilities for data visualisation and analysis are great in number (and are still increasing), which in the forensic context where the collected evidence is presented in court to support decision making is a significant advantage over a total station. The obtained 3D data can also easily be compared and fused with other data about the site (De Reu et al. 2014: 261). For example, the volume of tool or tire marks found during the excavation can be measured from a 3D model to identify the tool or tire model that inflicted the marks.

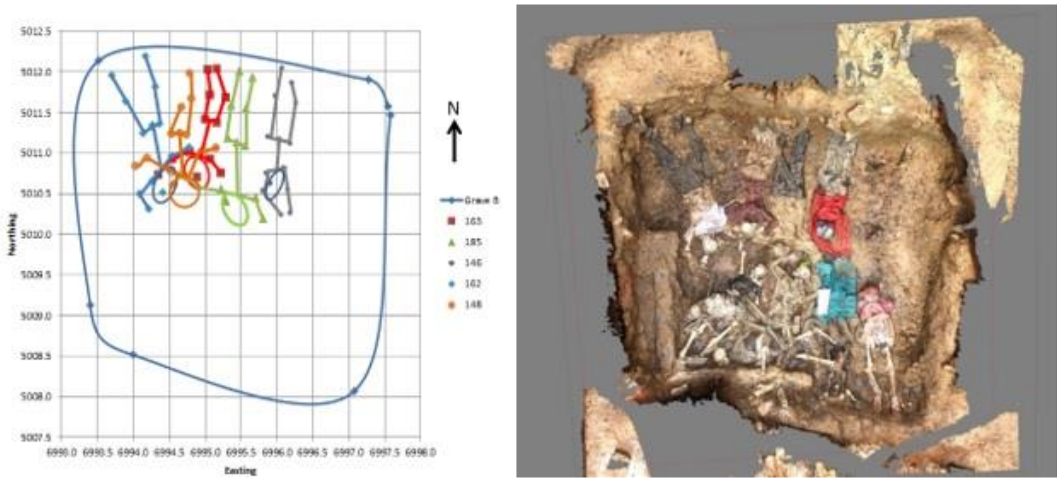



***Figure 12***. *Comparison of the outputs of the simulated mass grave generated from total station (left) and photogrammetric data (right).*

Mass graves often relate to atrocity crimes, and therefore their investigation may be complicated, for instance, by attempts to halt the excavation, or by reburying the victims elsewhere. Furthermore, if the mass grave is located in an area of ongoing conflict, the security and health of the investigators might be at risk. Hence, the use of time-consuming documentation methods in forensic mass grave excavation could not only lead to incomplete evidence collection, but could also jeopardize the security and health of the field staff. In such conditions, only time-efficient documentation methods should be used to keep the documentation phase as short as possible while still ensuring the complete and high quality evidence collection. Using photogrammetry, the documentation of an exposed layer in the simulated mass grave excavation could be completed in 5-10 minutes, depending on the number of images taken. With a total station, the same time was taken for documenting just one skeleton with 13 anatomical points, and more time was required for photography (cf., Baier and Rando 2016: 9; Howland et al. 2014; Seitsonen and Holappa 2011: 45). Because the simulated mass grave could be photographed at any scale from different viewing angles by just walking around the grave, the whole coverage of the simulated mass grave could be ensured without significantly prolonging the documentation phase. In addition, adjusting the camera settings for the prevailing brightness conditions at the time of photography was completed in a couple of minutes, while the calibration of the total station took 30-45 minutes. Total station surveying also tied two persons from other duties, whereas photogrammetric documentation could be performed singlehanded.

Although forensic mass grave excavations are usually initiated by international bodies, such as the International Criminal Tribunal for the former Yugoslavia (ICTY), time and economic constraints for field work often exist. This is likely the reason why expensive technology, such as laser scanners, is not commonly used in forensic mass grave excavations. While a total station is commonly used for site documentation in forensic mass grave excavations, the cost of a total station instrument, and field time required for a more detailed documentation of the scene could become an issue in excavations with more limited resources. Therefore, another advantage of photogrammetry is that it is a very low-cost method in the field: A consumer grade single-lens reflex camera can be used for obtaining accurate spatial information of the site with minimum field-time. Furthermore, there are several semi- or fully automated open source and commercial software available for more time-efficient image processing, although further research is required to determine their applicability to the forensic context.

The generation of accurate and high quality 3D models, however, can be computationally expensive, especially if large image sets and algorithms capable of generating very dense point clouds are used (cf., Fonstad et al. 2013: 428). Therefore, such 3D models cannot be generated with a standard laptop scale computer. Nevertheless, the costs of high performance computers and commercial photogrammetric software, potentially more suitable for the forensic context, remain much lower than the cost of a total station. For more general advantages of photogrammetry, see, e.g., Micheletti et al. 2015; De Reu et al. 2014.

Based on the field experiment, photogrammetry proved to be a low-cost, time-efficient and non-invasive documentation method that could easily be integrated into the general workflow of a forensic mass grave excavation, once included in the documentation strategy (see also, De Reu et al. 2014; Forte et al. 2012). Photogrammetry was found to prevail over a total station, the commonly used documentation method in forensic mass grave excavations, in documentation speed and coverage, richness of record, and in cost- and time-efficiency. The mass grave could also be documented from a distance, unlike if a total station was used, and thus, no evidence was destroyed or its *in situ* position and context changed during the documentation. Hence, the integrity of evidence could be protected during the documentation. In terms of accuracy, photogrammetry has found to be similar with laser scanning (e.g., Rüther et al. 2012; Doneus et al. 2011; Barazzetti et al. 2009; El Hakim et al. 2008; Remondino et al 2008).

### 3.3 Disadvantages of Photogrammetry

While there are numerous advantages of photogrammetry, there are also disadvantages and limitations of the method that should be taken into account when applying it to the forensic context. Due to the high computing power and memory required for photogrammetric image processing, the quality and coverage of photogrammetric recordings cannot be checked right after the recording. Furthermore, because photogrammetry is an optical method, its use is limited by environmental factors: photogrammetry does not perform well in the rain or snow, and requires consistent and adequate lighting conditions, as rain droplets, snowflakes, and inconsistent textures due to brightness variation could confuse image matching process; photogrammetry cannot be used in the dark.

Photogrammetric image processing, i.e., the generation of photogrammetric outputs, requires a lot of computing power and memory, and thus the 3D model of the site can only be obtained with a delay. Therefore, the results of photogrammetric processing cannot be checked right after the documentation to ensure sufficient coverage and imaging geometry, and to identify the needs for additional images. Hence, the importance of a well-planned image acquisition and making field notes are highlighted. In some occasions, for instance, if the excavation is disrupted for a few hours, this disadvantage can be overcome by generating low resolution 3D models from the acquired images (De Reu et al. 2014: 245, 259), or at least aligning the images immediately after photography to check that the gathered photographic record and imaging geometry are sufficient and reliable. Nevertheless, making field notes about the findings is important, in case some of the findings were not properly documented or cannot be rendered visible from the images due to their extremely subtle visual appearance. Making field notes is also important for another reason: as with photography, with photogrammetry, rendering extremely subtle variations in the ground or features is difficult, especially if lighting conditions are not ideal, and hence the field notes might remain the only record of minute variations noticed during an excavation.

Photogrammetry, as photography in general, is an optical method, and therefore lighting and weather conditions during documentation affect both the accuracy and visual appearance of the 3D model of an object. Having sufficient and consistent lighting and weather conditions is especially critical if SfM approach is used, because it relies on automatic feature matching (e.g. SIFT algorithm relies on multiscale image brightness and colour gradients in point identification and matching, Lowe 1999) (for further limitations of SfM approach, see, Remondino et al. 2012). Changes in lighting, as well as rain droplets and snowflakes, can lead to mismatches during feature matching process, resulting in inaccurate camera calibration and, consequently, inaccurate outputs. Taking photographs in too dark or too bright lighting may result in the lack of contrast in the images and reduced textural detail, which will lead to the subtle variations in the ground or features to be saturated from the images, and, as shown by Micheletti et al. (2014: 484), yield lower density point clouds and more uncertain point qualities. Also the use of flash is discouraged, as it produces inconsistent image textures, possibly confusing the feature matching process. Furthermore, since the features used in image matching process are extracted from all the images in the image set used as input, it is fundamental that light between frames is consistent. (*ibid.*)

Sometimes, however, these aspects cannot be avoided during photography. In the field experiment, despite the use of a fixed aperture and adjusted shutter speed according to the prevailing lighting conditions, brightness differences could not be excluded from the images of some layers, and, consequently, the generated photogrammetric outputs (Figure 13). Therefore, masking and enhancing images according to, for example, SWGIT Best Practices for Documenting Image Enhancement standard, or another relevant standard, might be required before subjecting them to photogrammetric image processing to ensure high quality image matching process. The use of a camera with high dynamic range could also improve the image acquisition in varying lighting conditions.

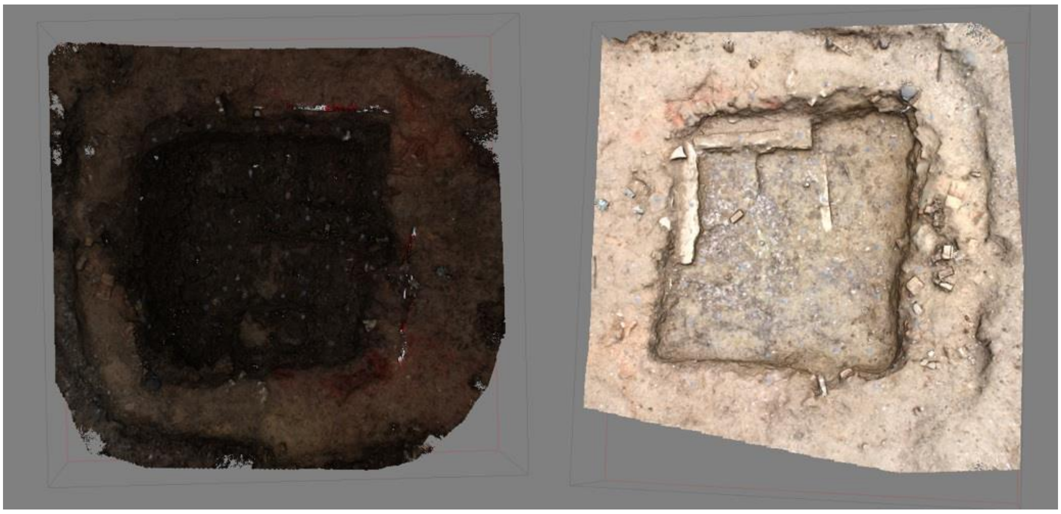


***Figure 13.*** *3D models of Layers 3 (left) and 7 (right). Varying lighting conditions during photography of different layers were also visible in the generated 3D models.*

# 4 Photogrammetry in the Forensic Context

## 4.1 Requirements for Admissible Scientific Evidence

According to the Daubert Standard and Rule 702, admissible scientific evidence (and the theory and method from which it was derived) should 1) be empirically testable; 2) have been subjected to peer review and publication; 3) have its known or potential error rate established, and have existing, maintained standards controlling its operation; 4) have attracted widespread acceptance within a relevant scientific community (i.e., Daubert factors; *Daubert v. Merrell Dow Pharmaceuticals, Inc*. 1993); (5) be based on sufficient facts or data; and (6) be the product of reliable principles and methods, which (7) have also been reliably applied to the facts of the case (Fed. R. Evid. 702).

To provide the reader with the exact definitions of the Daubert factor as initially conceived by the Supreme Court, the definitions are quoted in full:

*Factor 1: whether the theory or technique in question can be and has been tested*

"Ordinarily, a key question to be answered in determining whether a theory or technique is scientific knowledge that will assist the trier of fact will be whether it can be (and has been) tested. "Scientific methodology today is based on generating hypotheses and testing them to see if they can be falsified; indeed, this methodology is what distinguishes science from other fields of human inquiry." Green 645. See also C. Hempel, Philosophy of Natural Science 49 (1966) ("[T]he statements constituting a scientific explanation must be capable of empirical test"); K. Popper, Conjectures and Refutations: The Growth of Scientific Knowledge 37 (5th ed. 1989) ("[T]he criterion of the scientific status of a theory is its falsifiability, or refutability, or testability") (emphasis deleted)." (*Daubert v. Merrell Dow Pharmaceuticals, Inc*. 1993: 593.)

*Factor 2: whether it has been subjected to peer review and publication*

"Another pertinent consideration is whether the theory or technique has been subjected to peer review and publication. Publication (which is but one element of peer review) is not a sine qua non of admissibility; it does not necessarily correlate with reliability, see S. Jasanoff, The Fifth Branch: Science Advisors as Policymakers 61–76 (1990), and in some instances well-grounded but innovative theories will not have been published, see Horrobin, The Philosophical Basis of Peer Review and the Suppression of Innovation, 263 JAMA 1438 (1990). Some propositions, moreover, are too particular, too new, or of too limited interest to be published. But submission to the scrutiny of the scientific community is a component of "good science," in part because it increases the likelihood that substantive flaws in methodology will be detected. See J. Ziman, Reliable Knowledge: An Exploration of the Grounds for Belief in Science 130–133 (1978); Relman & Angell, How Good Is Peer

Review?, 321 New Eng. J. Med. 827 (1989). The fact of publication (or lack thereof) in a peer reviewed journal thus will be a relevant, though not dispositive, consideration in assessing the scientific validity of a particular technique or methodology on which an opinion is premised." (*Daubert v. Merrell Dow Pharmaceuticals, Inc*. 1993: 593-594.)

*Factors 3: its known or potential error rate and the existence and maintenance of standards controlling its operation*

"Additionally, in the case of a particular scientific technique, the court ordinarily should consider the known or potential rate of error, see, e. g., United States v. Smith, 869 F. 2d 348, 353–354 (CA7 1989) (surveying studies of the error rate of spectrographic voice identification technique), and the existence and maintenance of standards controlling the technique's operation, see United States v. Williams, 583 F. 2d 1194, 1198 (CA2 1978) (noting professional organization's standard governing spectrographic analysis), cert. denied, 439 U. S. 1117 (1979)." (*Daubert v. Merrell Dow Pharmaceuticals, Inc*. 1993: 594.)

*Factor 4: whether it has attracted widespread acceptance within a relevant scientific community*

"Finally, "general acceptance" can yet have a bearing on the inquiry. A "reliability assessment does not require, although it does permit, explicit identification of a relevant scientific community and an express determination of a particular degree of acceptance within that community." United States v. Downing, 753 F. 2d, at 1238. See also 3 Weinstein & Berger 702[03], pp. 702–41 to 702–42. Widespread acceptance can be an important factor in ruling particular evidence admissible, and "a known technique which has been able to attract only minimal support within the community," Downing, 753 F. 2d, at 1238, may properly be viewed with skepticism.” (*Daubert v. Merrell Dow Pharmaceuticals, Inc*. 1993: 594.)

Daubert also involved an interpretation of the Rule 702 of the Federal Rules of Evidence, which further defined the factors by requiring that the testimony is based on sufficient facts or data, the testimony is the product of reliable principles and methods, and the expert has reliably applied the principles and methods to the facts of the case (Fed. R. Evid. 702).

As can be seen from above, the meaning of these factors was left, intentionally, rather vague and abstract to enable a flexible inquiry (*Daubert v. Merrell Dow Pharmaceuticals, Inc*. 1993: 594-595). However, the failure of the Supreme Court to provide explicit requirements for admissible scientific evidence, and guidelines for applying these factors has raised substantial debate in both state and federal trials. As the result, some states (e.g., Arizona) have even declined to follow the Daubert standard. The Daubert standard, however, was never meant to be a definitive checklist for deciding whether particular testimony was or was not admissible (*Daubert v. Merrell Dow Pharmaceuticals, Inc*. 1993: 593, 598), but rather provide the general principles relevant for scientific evidence. As such, the value of Daubert, including the requirements of Rule 702, for this thesis is to provide a framework under which the applicability of photogrammetry to the forensic context can be assessed.

## 4.2 Admissibility of Photogrammetry

Photogrammetry has long been recognized as a reliable science by courts, and its admissibility is established (e.g., *Heatherly vs. Alexander* 2005; *Waste Management of Alameda County, Inc. v. East Bay Regional Park District* 2001; *Napeahi vs. Wilson* 1996; *United States v. Quinn* 1994*; Goodman vs. Crystal River* 1987; *Missouri vs. Department of Army Corp. of Engineers* 1980; *Canal Authority of Florida v. Callaway* 1974). In the above mentioned cases, however, the admissibility of photogrammetry was not discussed, but rather taken for granted. Consequently, they bear little in terms of practical value for assessing the admissibility of photogrammetry and photogrammetric evidence. In order to understand how courts have applied evidentiary standards (i.e., Daubert and Rule 702) to photogrammetric evidence, and thus to determine the applicability of photogrammetry to forensic mass grave excavation, a number of court orders where the court admitted photogrammetric evidence after its admissibility had been challenged was reviewed. Challenges owing to procedural errors, irrelevancy of evidence, and failure of the witness to meet the requirements for expert witness (i.e., qualifications) are beyond the control of expert witness and cannot be attributable to photogrammetry. Therefore, only citations of reliability and ability to meet the evidentiary standards of Daubert and Rule 702 are considered in the following sections.

A reason cited in decisions to admit photogrammetric evidence was the use of scientifically valid and sufficiently reliable technique that based on reliable principals and methods. In *United States v. Quinn* (1994), the District court had concluded that the photogrammetric process used by the expert witness "was nothing more than a series of computer-assisted calculations that did not involve any novel or questionable scientific technique". The appellate court further found that the photogrammetric evidence was reliable as required by Rule 702, because the process used by the expert witness was scientifically valid and sufficiently reliable to be placed before the jury (*ibid.*).

In *United States v. Williams* (2007), the appellant challenged the reliability of photogrammetric evidence on the grounds that the technique fails to satisfy any of the five Daubert criteria (i.e., factors) for admission of expert testimony. In specific, the appellant argued that "the government failed to proffer evidence demonstrating the reliability of Smith's [expert witness] reverse projection photogrammetery technique as it was used in this case, including evidence that the technique has been published or subjected to peer review, evidence as to the technique's error rate, evidence as to the standards controlling the technique's operation, or evidence that the technique, as used in this case, is accepted by anyone outside of the FBI". The District court had admitted the evidence, because it had found that the testimony was based on sufficient facts or data, was a product of reliable principals and methods, and that the witness had applied the principals and methods reliably to the facts of the case. The appellant court affirmed the conclusions of the District court and highlighted that "all of the Daubert do not necessarily apply to each case nor are these factors a comprehensive list of all possible measures of reliability". Furthermore, the appellant court affirmed that a detailed explanation of the technique of reverse projection photogrammetery had been provided, the methodology used in the technique and how the methods were applied in this case were explained in detail, the technique had been published, and that it was employed by the FBI and other law enforcement agencies. Based on this evidence, the appellant court concluded that the used photogrammetric technique was sufficiently reliable to satisfy the admission requirements of Rule 702, and was therefore admissible. (*United States v. Williams* 2007.)

In *United States v. Kyler* (2011), the appellant argued that the District court had admitted photogrammetric evidence against the Daubert requirements. The appellant court found that the appellant could not establish an error, because he had not referred to any previous case where the photogrammetric technique had been rejected as not sufficiently reliable under Daubert. In its decision, the apellant court referred to the decision of the Ninth Circuit in *United States v. Quinn* (1994) of upholding the admission of expert testimony based on photogrammetry as sufficiently reliable under Daubert. (*United States v. Kyler* 2011.)

In another case, *Papadolous v. Fred Myers Stores* (2006), the court found photogrammetric evidence reliable, because the expert witness's measurements could be and had been tested, they could be reliably replicated, the known or potential error rate for measurements was low, and the expert witness demonstrated the reliability of the measurements through examples. The court also noted that there was no dispute that close range photogrammetry has been subjected to peer review and publication or that close range photogrammetry enjoys general acceptance within the relevant scientific community. The court supported its conclusion by referring to the fact that courts have previously admitted testimony based on photogrammetry (the court referred to *United States v. Quinn* 1994). The court, however, had some concern under Rule 702(2) of the Federal Rules of Evidence that "the testimony is based on sufficient facts or data", due to the resolution of the photographs used by the expert witness. As a result, both the plaintiffs and the defendant were given broad discretion to present and contest the factual foundation (including data) of the expert witness's testimony. (*Papadolous v. Fred Myers Stores* 2006.)

To summarize, photogrammetric evidence has been admitted in court, if:

- the witness had used a scientifically valid and sufficiently reliable technique, or a technique that was not novel (*United States v. Quinn* 1994)
- it was based on sufficient facts or data; it was a product of reliable principals and methods; the witness had applied the principals and methods reliably to the facts of the case; the witness explained the technique and methods in detail and how they had been applied in the case in question; the technique had been published; and that it was widely used by the relevant community (*United States v. Williams* 2007)
- it had been previously admitted in court (*United States v. Kyler* 2011; *Papadolous v. Fred Myers Stores* 2006)
- the expert witness's measurements could be and had been tested, they could be reliably replicated, the known or potential error rate for measurements was low, and the expert witness demonstrated the reliability of the measurements (*Papadolous v. Fred Myers Stores* 2006)

Although photogrammetry is common practice in the forensic context (see 1.2.2), and it has been accepted as evidence in court under Daubert and Rule 702, a specific application of photogrammetry or technique might not be automatically admissible

(Page et al. 2011: 915-917[4]; cf., *United States v. Quinn* 1994[5]). For example, the Daubert standard requires that scientific method or technique can be and has been tested, it has been subjected to peer review and publication, its error rate is known, there are standards controlling its operation, and that it has attracted widespread acceptance within a relevant scientific community. Even though the scientific evidence does not have to satisfy all the above mentioned factors (*United States v. Williams* 2007; see also, *Kannankeril v. Terminix Int'l, Inc*. 1997[6]), with novel scientific methods it might be difficult to satisfy even one of them. As a method must first be tested, published, and generally accepted by the relevant scientific community, novel methods can only be admissible in court with a delay (cf., *Ramirez v. State* 2001).

Indeed, regardless the acknowledged benefits of advanced photogrammetric methods, especially those developed in the computer vision science, their application in the forensic context is severely complicated by the strict requirements for admissible scientific evidence. For example, based on the literature review, the Structure-from-Motion method applied in the field experiment has never been introduced as evidence in court (see also, Baier and Rando 2016), and thus its ability to satisfy the evidentiary requirements has not been defined. The field experiment provided evidence supporting its admissibility, however, some practical concerns, and concerns under Daubert and Rule 702 were identified that must be solved, if this approach was to be applied to forensic mass grave excavation.

[4] See, *United States v. Green* 2005; *United States v. Sullivan* 2003*; Government of the Virgin Islands v. Austin Jacobs* 2002, and *United States v. Saelee* 2001.

[5] The Court concluded that photogrammetric process used by the expert witness "did not involve any novel or questionable scientific technique".

[6] The Court hold that lack of peer review or publication was not dispositive where the expert's opinion was supported by "widely accepted scientific knowledge".

## 4.3 Photogrammetry and Evidentiary Requirements

### 4.3.1 Evidentiary Requirements for Photogrammetric Image Processing

*Software*

Based on the review of favorable decisions on admissibility, the reliability of photogrammetry relies on the ability to explain both the technique and methodology in detail and how they were applied in the case in question (see, *United States v. Williams* 2007). Although the photogrammetric 3D reconstruction and the underlying theory about the relationship of a 3D object and 2D images can be explained in detail and supported by a vast number of publications, the reliability of evidence could be challenged if 'black box' software was used for photogrammetric image processing.

In the field experiment, semi-automatic PhotoScan (Agisoft) software was used for image processing, because it had been appraised for its performance, and accurate and high quality outputs. The software, however, was found to be a 'black box' tool that provided no explicit knowledge of the underlying mathematical or theoretical models, algorithms or parameters used in 3D reconstruction of the simulated mass grave. Furthermore, while the software provided error estimates for the image alignment (i.e., the reprojection error and effective overlap estimate; see, Appendix 2), the way how these were computed remained unclear. Therefore, it was impossible to define the applied methodology, or evaluate the reliability of the method or the generated outputs.

Furthermore, while it was possible to document the software settings used in each image processing phase, along with the obtained results (e.g., number of points in a dense point cloud; see, Appendices 1 and 2), and hence the 3D reconstruction could be repeated by another examiner using the same images, software and software settings, the validation of the technique by another examiner would be impossible due to the 'black box' nature of the software. The underlying theoretical models, algorithms or parameters used in, for instance, estimating camera parameters or lens distortions, or in generating the outputs of each processing phase were not disclosed at any stage of the processing. For this reason, testing or establishing the scientific validity of the technique would be impossible, as the necessary parameters for this could not be accessed.

As evidenced by the field experiment, by using ‘black box’ software, such as PhotoScan, it would be impossible to (1) explicitly explain the technique and methodology, and how they were applied in the case in question, nor (2) to establish its reliability for the specific forensic application. Inability to fully explain the applied technique and methodology, and to establish its reliability has led to the exclusion or restriction of evidence. In *State v. Swinton* (2004), the court restricted the use of photogrammetric evidence, because the expert witness could not explain the inner workings of the software used for image processing and could not determine the reliability of the software for the specific forensic application. Furthermore, in *State of Maryland v. Bryan Rose* and *Commonwealth v. Patterson*, fingerprint evidence was excluded because the prosecutions failed to demonstrate that the scientific validity of specific methodology had been tested (Page et al. 2011: 915).

The use of ‘black box’ software, and the consequent inability to clearly define the underlying theoretical models and parameters, and how they were applied to 3D reconstruction (i.e., the inner workings of the software, and the reliability of the software) would inevitably lead to the exclusion of the generated photogrammetric evidence. Therefore, its use is not recommended in forensic mass grave excavations. Instead, a software that discloses the theoretical models, algorithms and parameters used in 3D reconstruction and is capable of producing consistent results (SWGIT Guidelines for Image Processing, 29.3.2016; cf., Daubert factor 1) should be used. If automated image processing is however applied, the practitioner must know how and that the application works (i.e., understand the basic principles of the software and the effects of changing settings within the software), and know the limits of the application. Moreover, the use of a particular software application must be validated for its intended purpose. (SWGIT Best Practices for Automated Image Processing, 30.3.2016.)

*Image Processing*

One of the requirements for admissible evidence under Daubert is the existence and maintenance of standards controlling its operation. In fact, a failure to adhere to recognized standards has resulted in the rejection of evidence. According to the court decision in *State v. Swinton* (2004), "[i]n addition to the reliability of the evidence itself, what must be established is the reliability of the procedures involved, as defense counsel must have the opportunity to cross-examine the witness as to the methods used". Because the expert witness could not cite specific procedures followed in image processing, the use of photogrammetric evidence was restricted (*ibid.*). Furthermore, in *Ramirez v. State* (2001), tool mark expert's evidence was excluded, because there were no objective standards governing the expert's method. Similarly, in *Bourne v. Town of Madison* (2007), the court excluded evidence, because the expert's methodology of enlargement of the specimen was "inconsistent with the accepted methodology among forensic document examiners" (Page et al. 2011: 915).

Although each photogrammetric software has its own requirements for image acquisition and its own image processing workflow, there are also standards for forensic photogrammetry and image processing that must be followed to ensure the admissibility of evidence in court. For example, Scientific Working Group on Digital Evidence (SWGDE), the members of which include several police departments and other law enforcement in the United States, has proposed a set of standards for image processing, documentation and data management (see, SWGIT Documents) that implement the evidentiary requirements of Daubert and Rule 702.

The first requirement often cited in admission decisions and standards governing the use of digital evidence is that the original data must not be altered (e.g., *State v.*

*Swinton* 2004; SWGIT Guidelines for Image Processing, 29.3.2016; ACPO Good Practice Guide for Digital Evidence). Instead, working copies should be generated for processing. Second, all processes applied to digital images should be documented and the record preserved (cf., *State of New Hampshire v. Richard Langill* 2008*; United States v. Monteiro* 2006*; Ramirez v. State* 2001; Daubert factor 1). Third, an independent third party should be able to repeat the process and arrive at the same result (Daubert factor 1). Moreover, according to the SWGDE Best Practices for the Forensic Use of Photogrammetry, the basis for, and uncertainty of, any conclusions should be documented and reported, including identified sources of uncertainty (and potential error).

As can be seen above, there are no specific limitations on the image processing *per se*, provided that the original image[7] is preserved, processing steps are documented "in a manner sufficient to permit a comparably trained person to understand the steps taken, the techniques used, and to extract comparable information from the image" (SWGIT Guidelines for Image Processing, 29.3.2016; see also, SWGIT Best Practices for Documenting Image Enhancement, 21.3.2016), and the process is explained to the jury (*State v. Swinton* 2004; SWGIT Guidelines for Image Processing, 29.3.2016). The requirement of authenticity of evidence (i.e., Rule 901 of the Federal Rules of Evidence) that the proponent must produce evidence sufficient to support a finding that the item is what the proponent claims it is (Fed. R. Evid. 901a), on the other hand, might introduce some limitations on photogrammetric 3D reconstruction: Although in the case of images, as well as computer generated evidence, this requirement is usually satisfied with a witness testifying that the image accurately represents the scene or objects that were captured (*State v. Swinton* 2004) or that the evidence is a "fair and accurate representation of the evidence to which it relates'' (*Clark v. Cantrell* 2000), its implications for photogrammetric 3D reconstruction must be carefully considered.

[7] According to the Federal Rule of Evidence 1001(d), "original" means any printout — or other output readable by sight — if it accurately reflects the information".

In terms of photogrammetric evidence, the authenticity requirement of the Rule 901a requires in practice that the generated photogrammetric output or visualization of photogrammetric data accurately represents the scene or objects that were captured (cf., Fed. R. Evid. 901a; *State v. Swinton* 2004; *Clark v. Cantrell* 2000; SWGIT Best Practices for Maintaining the Integrity of Digital Images and Digital Video, 31.3.2016). In 3D reconstruction, 2D image points are returned into the original 3D location of the object applying established photogrammetric principles, but in the process some interpolation and approximation of data is required, and thus the authenticity of the generated photogrammetric outputs might be challenged in court.

For example, the PhotoScan software, used in the field experiment, applies filters during dense point cloud generation to sort out outliers among the points (Agisoft LCC 2014). The use of filters, however, might also sort out meaningful details in the scene, and therefore the generated dense point cloud might not accurately represent the scene that was captured. Furthermore, in mesh (i.e. 3D model) generation, the 3D points of a dense point cloud are connected to form a network of triangles, a polygonal model approximating the shape of the object (AgiSoft LCC 2014), the resolution of which depends on the settings selected by the operator. Therefore, the generated 3D model is an approximation of the object, a sort of interpretation by the software derived from the dense point cloud, while the dense point cloud represents the computed 3D object points. If only the relative location of evidence and its context is of interest in legal proceedings, then a dense point cloud along with the original images might better satisfy the authenticity requirement than a 3D model. However, if a 3D model is required for, for example, performing volumetric measurements, the authenticity of the 3D model must be proven.

The authenticity requirement for admissible evidence (i.e., Rule 901) might also limit editing of photogrammetric outputs (i.e., dense point cloud, 3D model, etc.). While enhancing and masking images and removing areas that are not of interest from the generated dense point cloud might well be acceptable measures under the evidentiary standards of Daubert and Rule 702, provided that they are documented in detail and performed according to an established standard, any measure introducing something that was not present in the original images to the final output will most certainly lead to the rejection of photogrammetric evidence based on Rule 901. For example, PhotoScan software has a tool with which holes in the generated 3D model (i.e., mesh) can be closed to achieve a more appealing visualization. In doing so, however, the missing data is replaced with interpolated data and thus, something that was not in the original images is introduced to the generated output.

Furthermore, photogrammetric image processing generates very large files, the archiving and presentation of which require a lot of computer memory and power. Therefore, some sort of decimation might be required to enable the presentation of evidence in court and the long-term archiving of digital evidence. Decimation, whether referring to the reduction of points or polygons in a dense point cloud or a 3D model (as in PhotoScan) or to the compression of a file, to reduce file size, however, always reduces the amount of information and hence, might result in loss of evidence. In the forensic context, decimation must therefore be avoided whenever possible (see also, SWGIT Guidelines for Image Processing, 29.3.2016).

### 4.3.2 Integrity and Authenticity of Photogrammetric Evidence

In the forensic context, protecting the integrity of evidence is vital, as if in doubt, the evidence could be rejected in court, possibly preventing the conviction of perpetrator(s). Specific procedures for handling and storing evidence to protect integrity of evidence exist, however, the digital format of evidence has introduced new elements of uncertainty into the protection of integrity that are relevant also to photogrammetric evidence.

The rapid advances in digital technology introduce uncertainty also into the long-term preservation of digital data due to short media life, obsolete hardware and software, and slow read times of old media. Furthermore, there are no proven methods to ensure that the collected digital evidence will continue to exist, that it can be accessed in the future, or that the accessed evidence is authentic and reliable. (Chen 2001: 24.)

In the forensic context, there is a fundamental paradox for digital preservation: while digital evidence must be maintained intact, it must also be accessible in the future (see also, SWGIT Overview of SWGIT and the Use of Imaging Technology in the Criminal Justice System, 31.3.2016). In long-lasting legal proceedings, such as those regarding evidence recovered from mass graves, sustained accessibility to digital evidence is paramount, as the evidence might have been collected many years earlier to its presentation in court. However, as Chen (2001: 25) highlights, accessing digital evidence without modifications will become more difficult, if not impossible, because of obsolete hardware and software (cf., SWGIT Overview of SWGIT and the Use of Imaging Technology in the Criminal Justice System, 31.3.2016). In the forensic context where the admissibility of photogrammetry and photogrammetric evidence relies on preserving the original, unaltered images from which the evidence was derived, the problem is then how to ensure long-lasting preservation of unmodified images and the derived photogrammetric evidence in the era of rapid technological developments? This is an issue beyond the scope of this thesis, which has to be solved in the future if photogrammetry was to be applied to forensic mass grave excavations.

In practical terms, the requirement of long-lasting preservation of images and the derived photogrammetric evidence is a matter of computer storage, as the data amount collected and generated during a forensic mass grave excavation is enormous. Therefore, the limitations in computer storage capacity, in combination with the requirement of long-lasting data preservation, affect the required level of processing and the outputs that must be preserved for future access: While 3D models generated with a specific software might be visually most appealing, their accessibility with other software, especially in the future, cannot be guaranteed. Therefore, along with the original, uncompressed images, and the generated 3D models (or whatever the final output might be), also TIFF conversions of the original images must be saved, so that they can be accessed and, if necessary, re-processed in the future with other software. Specific recommendations relating to archiving may be found, for instance, in the SWGIT document *Best Practices for Archiving Digital and Multimedia Evidence (DME) in the Criminal Justice System*.

The more critical issues regarding photogrammetry in the forensic context are the integrity of digital evidence and the authentication of preserved digital data, the legal prerequisites to the admissibility of any evidence (Fed. R. Evid. 901). Integrity ensures that the digital evidence presented in a court of law is complete and unaltered from the time of acquisition until its final disposition. To secure and maintain integrity of digital evidence requires that each step in the workflow is carefully and accurately documented, and the security of the files ensured at all times, as digital evidence can be easily manipulated. (SWGIT Best Practices for Maintaining the Integrity of Digital Images and Digital Video, 31.3.2016). In terms of photogrammetry, manipulation of images, however, can be detected, as it results in error in the camera calibration. Moreover, procedures and methods for demonstrating integrity must be in place in case the integrity is challenged in court (see, e.g., SWGIT Best Practices for Maintaining the Integrity of Digital Images and Digital Video, 31.3.2016).

Authentication, on the other hand, is "the process of substantiating that the content is an accurate representation of what it purports to be" (SWGIT Best Practices for Maintaining the Integrity of Digital Images and Digital Video, 31.3.2016). According to the Rule 901 (a) of the Federal Rules of Evidence, "[t]o satisfy the requirement of authenticating or identifying an item of evidence, the proponent must produce evidence sufficient to support a finding that the item is what the proponent claims it is" (Fed. R. Evid. 901a). Furthermore, Rule 901 (b) (9) provides that authentication or identification of a process or system requires ''[e]vidence describing a process or system used to produce a result and showing that the process or system produces an accurate result'' (Fed. R. Evid. 901b). Hence, in *State v. Swinton* (2004), the court concluded that "the federal rule dictates that the inquiry into basic foundational admissibility requires sufficient evidence to authenticate both the accuracy of the image and the reliability of the machine producing the image". In the case of images the authentication requirement is usually satisfied with a witness testifying that the image accurately represents the scene or objects that were captured (*State v. Swinton* 2004; *Clark v. Cantrell* 2000 holding computer generated evidence admissible where it is, among other things, a ‘‘fair and accurate representation of the evidence to which it relates’’).

If the authenticity of the digital evidence is challenged, evidence showing that the image has not been altered might be required (SWGIT Overview of SWGIT and the Use of Imaging Technology in the Criminal Justice System, 31.3.2016). For example in *State v. Swinton* (2004), the court concluded that authentication under Rule 901 can be established by providing evidence that " (1) the computer equipment is accepted in the field as standard and competent and was in good working order, (2) qualified computer operators were employed, (3) proper procedures were followed in connection with the input and output of information, (4) a reliable software program was utilized, (5) the equipment was programmed and operated correctly, and (6) the exhibit is properly identified as the output in question".

# 5 Conclusions

The aim of this thesis was to determine the applicability of photogrammetry to forensic mass grave excavations and the forensic context in general. The applicability was investigated by testing photogrammetry in practice in a simulated mass grave excavation where photogrammetry was not a part of documentation strategy, and by comparing photogrammetry and the generated outputs of the simulated mass grave with the requirements for admissible scientific evidence outlined in the Daubert standard and Rule 702 of Federal Rules of Evidence. A number of court decisions on the admissibility of photogrammetry was reviewed to determine the admissibility and hence, the applicability of photogrammetry to forensic mass grave excavations.

Based on the field experiment, the evidentiary requirements and how they have been applied to photogrammetry, photogrammetry was found to be more suitable method of documentation in forensic mass grave excavation than the currently used method of a total station. Photogrammetry prevailed a total station in documentation speed and coverage, richness of record, and in possibilities to analyse and present evidence in court. In addition, with photogrammetry, the simulated mass grave could be documented from a distance (i.e., a non-invasive method), and thus the integrity of evidence could be preserved during documentation. In the forensic context, the integrity of evidence is critical, as if in doubt, its use in legal proceedings could be jeopardized and the conviction of the perpetrator(s) precluded.

Photogrammetry was found to be a time-efficient method that enabled the complete, accurate and detailed documentation of a simulated mass grave in a short period of time. The use of a time-efficient documentation method in forensic mass grave excavation is especially important if the mass grave is located in conflict or otherwise vulnerable areas, as the documentation of evidence might suddenly be disrupted by, for instance, an armed attack. In such conditions, the use of time-consuming methods, such as a total station, not only jeopardizes the complete documentation of evidence, but also puts the security and health of the investigators at risk.

Another significant advantage of photogrammetry in the forensic context is that it is an objective method in terms of evidence collection: with photogrammetry, everything visible for the camera is recorded as infinitive number of points, along with its visual appearance. As the result, with photogrammetry, the conditions in the field, including the recovered evidence and its *in situ* context, can be accurately and reliably represented to the court in the form of, for instance, a photorealistic 3D model that can be zoomed and rotated. For example, in the field experiment, the tire marks visible in the ground over and around the simulated mass grave were also visible in the generated 3D model. In the forensic context where the purpose of collecting evidence is to provide sufficient factual basis for establishing the criminal responsibility, the use of a documentation method that is capable of representing the mass grave scene as it was captured is not only required (by the Rule 901 of the Federal Rules of Evidence), but also necessary for facilitating the legal assessment.

Although photogrammetry was found to prevail the currently used documentation method in forensic mass grave excavation, a total station, some practical concerns and concerns under Daubert and Rule 702 were identified that must be solved before photogrammetry could be applied to forensic mass grave excavation.

In the field experiment, photogrammetry did not fit seamlessly to the general workflow of the simulated mass grave excavation, because it had not been included in the pre-defined documentation strategy and the strategy could not be modified to meet the requirements for successful photogrammetric documentation. Consequently, the image quality was decreased by the varying lighting conditions during photography, and in some images, the view of the simulated mass grave was blocked by the field staff and tools. Hence, extra effort was required in image processing in order to ensure high quality photogrammetric outputs.

The above mentioned issues, however, could be solved by including photogrammetry in the documentation strategy of the excavation, and in practice, by performing photogrammetric image acquisition simultaneously with the crime scene photography. In that way, the scene would be prepared, without extra effort, for both photogrammetric documentation and crime scene photography, and the excavation would not be unnecessarily halted with an extra documentation phase.

Moreover, since the same lighting requirements apply also to the crime scene photography, the high quality of images for photogrammetric processing is ensured by the standard measures normally used during photography. If consistent and sufficient lighting conditions however could not be ensured during photography, and hence the acquired images show significant brightness variations, the use of a camera with high dynamic range and the removal of brightness variations from the images before photogrammetric image processing could improve the quality of the subsequent photogrammetric outputs. Nevertheless, the original images must be preserved, relevant standards for image enhancement followed, and the image processing steps documented in detail to ensure the admissibility of photogrammetric evidence.

Photogrammetric image processing requires a lot of computing power and memory, although processing times can be reduced by processing images as subsets according to, for instance, excavation layers, as was done in the field experiment. Therefore, the quality and completeness of photogrammetric record can only be checked with a delay. Since excavation cannot be halted until the photogrammetric data is processed, another way of checking the record must be found. In some occasions, this problem can be overcome by processing images immediately after the recording into a robust 3D models for next-day use. This approach, however, does not solve the problem of how to complete image data in case the robust 3D model indicates a poor coverage of the mass grave or a weak imaging geometry. Therefore, it is recommended that the images (or image subsets representing different excavation layers) are at least aligned and a sparse point cloud generated (can be done within 30 minutes or so) right after photography, so that additional images can be taken if necessary. In addition, the visual quality of images should be checked after each image to ensure that the lighting conditions remain consistent, images are in focus, and that a sufficient overlap between the images and the full coverage of the grave are achieved. Nevertheless, the importance of a well-planned image acquisition and making field notes cannot be overemphasized, as the above mentioned measures can only solve the problem to a point.

Furthermore, in the field experiment, a semi-automatic software PhotoScan (Agisoft), commonly used in other disciplines (for instance, archaeology), was used for photogrammetric image processing. During photogrammetric image processing it became clear, however, that it was ‘black box’ software, the inner workings of which could not be defined. Therefore, regardless its common use in other sciences, it was not suitable for the forensic context; it could not meet the requirements for admissible scientific evidence. In the forensic context, the requirements for admissible scientific evidence require that both the technique and methodology and how they were applied in the case in question can be explained in detail, image processing steps are documented in such a detail that an independent third party would be able to repeat the process and arrive at the same result or to understand the steps taken, the techniques used, and to extract comparable information from the image, and that the uncertainty of any conclusions is reported and their sources identified. Therefore, if photogrammetry is applied to forensic mass grave excavation and the recorded evidence presented in a court of law, a software capable of satisfying these requirements must be used. In other words, the use of 'black box' software without explicit knowledge of the underlying mathematical or theoretical models, algorithms, or parameters used in 3D reconstruction must be avoided in the forensic context. Image processing must also be performed according to established standards, so that the achieved results are verifiable and comparable, and that the reliability of the applied procedures can be established.

Finally, there is the question of how to present photogrammetric evidence, or how far images must be photogrammetrically processed to provide relevant and sufficient information for legal decision making without compromising the evidentiary requirement of authenticity (i.e., Rule 901). For example, it was found in the field experiment that PhotoScan software generates dense point clouds of such a high density that even the smallest details, such as tire marks, could already be seen from the generated point clouds, therefore obviating the generation of 3D models for presenting evidence. Dense point cloud represents the computed 3D location points of the original object, and therefore represents the original scene more accurately than a 3D model that is always an approximation of the 3D object surface. If the relative spatial location of evidence and its context is of interest, then a dense point cloud in combination with the original images might better satisfy the evidentiary requirements than a 3D model. The final output of photogrammetric processing, however, must always be determined according to the evidentiary needs of each case, and therefore no general recommendations can be made.

Based on this thesis, it can be concluded that photogrammetry prevails the currently used method of a total station as a documentation method in forensic mass grave excavation. In terms of admissibility then, the findings of this thesis indicate that the photogrammetric method used in the field experiment, Structure-from-Motion, is, if modified as proposed above, capable of satisfying the evidentiary requirements of the Daubert standard and the Rule 702 of the Federal Rules of Evidence. Its admissibility, however, can only be established once it has been introduced as evidence in a court of law.

# 6 References

*Research Literature:*


Alby, E., Elter, R., Ripoche, C., & Quere, N. 2013. Close Range Photogrammetry Applied to the Documentation of an Archaeological Site in Gaza Strip, Palestine. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences,* Vol. XL-5/W2: 19-24. XXIV International CIPA Symposium, 2.- 6.9.2013, Strasbourg, France.

Arnold, J., Bösch, H., & Braun, M. 2008. Reconstruction of a multi vehicle collision on a highway: Combining forensic evidence examination, 3D-scanning and 3D-photogrammetry with numerical accident reconstruction methods. International Research Council on the Biomechanics of Injury, International IRCOBI Conference on the Biomechanics of Injury, Proceedings pp. 433-436.

Baier, W. & Rando, C. 2016. Technical note: Developing the use of Structure-from-Motion in mass grave documentation. *Forensic Science International,* 261: 19-25.

Barazzetti, L. Remondino, F. & Scaioni, M. 2009. Combined use of photogrammetric and computer vision techniques for fully automated and accurate 3D modeling of terrestrial objects. *Proceedings of SPIE Optics+Photonics,* Vol. 7447. 2.-3.8.2009, San Diego, CA, USA.

Barsanti, S. G., Remondino, F., & Visintini, V. 2013. Surveying and modelling of archaeological sites: Some critical issues. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences,* 2(5/W1): 145-150.

Bradley, D., Boubekeur, T., Heidrich, W., 2008. Accurate multi-view reconstruction using robust binocular stereo and surface meshing. *Computer Vision and Pattern Recognition:* 1-8. IEEE Conference on Computer Vision and Pattern Recognition, 23.-28.6.2008, Anchorage, AK.

Brown, D. C. 1976. The bundle adjustment – progress and prospects. *International Archives of Photogrammetry*, 21(3).

Brown, D. C. 1971. Close-Range Camera Calibration. *Photogrammetric Engineering*, 37(8): 855-866.

Brown, D. C. 1966. Decentering distortion of lenses. *Photogrammetric Engineering*, 32(3): 444–462.

Callieri, M., Dell'Unto, N., Dellepiane, M., Scopihno, R., Soderberg, B., & Larsson, L. 2011. Documentation and interpretation of an archaeological excavation: an experience with dense stereo reconstruction tools. In: Dellepiane, M., Niccolucci, F., Pena Sema, S., Rushmeier, H., & Van Gool, L. (Eds.) *VAST 2011. 12th 332 International Symposium on Virtual Reality, Archaeology, and Cultural Heritage*, Eurographics Symposium Proceedings pp. 33-40.

Chen, S. 2001. The Paradox of Digital Preservation. *Computer*, 34(3): 24-28.

Cox, M., Flavel, A., Hanson, I., Laver, J., & Wessling, R. 2008. *The Scientific Investigation of Mass Graves. Towards Protocols and Standard Operating Procedures.* Cambridge University Press, Cambridge, UK.

De Reu, J., De Smedt, P., Herremans, D., Van Meirvenne, M., Laloo, P., & De Clerq, W. 2014. On introducing an image-based 3D reconstruction method in archaeological excavation practice. *Journal of Archaeological Science,* 41: 251-262.

De Reu, J., Plets, G., Verhoeven, G., De Smedt, P., Bats, M., Cherretté, B., De Mayer, W., Deconynck, J., Herremans, D., Laloo, P., Van Meirvenne, M., & De Clerq, W. 2013. Towards a three-dimensional cost-effective registration of the archaeological heritage. *Journal of Archaeological Science,* 40: 1108-1121.

Doneus, M., Verhoeven, G., Fera, M., Briese, L., Kucera, M., & Neubauer, W. 2011. From deposit to point cloud: A study of low-cost computer vision approaches for the straightforward documentation of archaeological excavations. *Geoinformatics,* 6: 81-88.

Ducke, B., Score, D., & Reeves, J. 2011. Multiview 3D reconstruction of the archaeological site at Weymouth from image series. *Computer & Graphics,* 35: 375-382.

El-Hakim, S., Beraldin, J.-A., Picard, M., & Cournoyer, L., 2008. Surface Reconstruction of Large Complex Structures from Mixed Range Data - The Erechtheion Experience. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XXXVII(Part B5): 1077-1082.

Epure, V. I. 2012. Height Measurement of Persons in Orthostatic Position Using Digital Images. *Romanian Journal of Forensic Science*, 83(5): 1120-1123.

Fisher, R., Dawson-Howe, K., Fitzgibbon, A., Robertson, C., & Trucco, E. 2005. *Dictionary of Computer Vision and Image Processing*. John Wiley & Sons, Hoboken.

Fonstad, M. A., Dietrich, J. T., Courville, B. C., & Carbonneau, P. E. 2013. Topographic structure from motion: a new development in photogrammetric measurements. *Earth Surface Processes and Landforms*, 20: 817-827.

Forte, M. 2014. 3D Archaeology. New Perspectives and Challenges – The Example of Çatalhöyük. *Journal of Eastern Mediterranean Archaeology and Heritgae Studies*, 2(1): 1-29.

Forte, M., Dell'Unto, N., Issavi, J., Onsurez, L., & Lercari, N. 2012. 3D Archaeology at Çatalhöyük. *International Journal of Heritage in the Digital Era*, 1(3): 351-378.

Fraser, C. 2015. Advances in Close-Range Photogrammetry. In: Fritsch, D. (Ed.) *Photogrammetric Week 2015* pp. 257-268. http://www.ifp.uni-stuttgart.de/publications/phowo15/260Fraser.pdf. Accessed 10.3.2016.

Fraser, C., Cronk, S., & Hanley, H. 2008. Close-range photogrammetry in traffic incident management. In: Chen, J., Jiang, J., & Maas, H-G. (Eds.) *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, Vol. XXXVII(Part B5): 125-128. XXIst ISPRS Congress, 3.-11.7.2008, Beijing, China. http://www.isprs.org/proceedings/XXXVII/congress/5_pdf/22.pdf. Accessed 10.3.2016.

Furukawa, Y. & Ponce, J. 2010. Accurate, dense, and robust multiview stereopsis. *IEEE Transactions on Pattern Analysis and Machine Intelligence,* 32: 1362–1376.

Fussell, A. 1982. Terrestrial photogrammetry in archaeology. *World Archaeology,* 14(2): 157-172.

Goesele, M., Snavely, N., Curless, B., Hoppe, H., & Seitz, S. M. 2007. Multi-View Stereo for Community Photo Collections. *Computer Vision*: 1-8. IEEE 11th International Conference on Computer Vision, 14.-21.10.2007, Rio de Janeiro, Brazil.

Haglund, W. D., Connor, M., & Scott, D. D. 2001. The Archaeology of Contemporary Mass Graves. *Historical Archaeology*, 35(1): 57-69.

Hartley, R. & Zisserman, A. 2004. *Multiple View Geometry in Computer Vision*. Cambridge University Press, Cambridge, UK.

Hartley, R. & Zisserman, A. 2003. *Multiple View Geometry in Computer Vision*. Second edition. Cambridge University Press, Cambridge, UK.

Hartley, R. & Zisserman, A. 2000. *Multiple view geometry in computer vision.* Cambridge University Press, Cambridge, UK.

Howland, M. D., Kuester, F., & Levy, T. E. 2014. Photogrammetry in the field: Documenting, recording, and presenting archaeology. *Mediterranean Archaeology and Archaeometry*, 14(4): 101-108.

James, M. R. & Robson, S. 2012. Straightforward reconstruction of 3D surfaces and topography with a camera: accuracy and geoscience application. *Journal of Geophysical Research*, 117(F3): 1-17.

King, C. G. & Ebert, J. I. 2002. Integrating Archaeology and Photogrammetry with Fire Investigation. *Fire Engineering*, February 2002: 79-84.

Konecny, G. 1996. Paradigm Changes in ISPRS from the First to Eighteenth Congress in Vienna. *ISPRS Highlights*, 1: 10-15.

Leipner, A., Baumeister, R., Thali, M. J., Braun, M., Dobler, E., & Ebert, L. C. 2016. Multi-camera system for 3D forensic documentation. *Forensic Science International*, 261: 123-128.

Lowe, D. G. 1999. Object recognition from local scale-invariant features. *The Proceedings of the International Conference on Computer Vision*, 2: 1150–1157.

Lynnerup, N., Sejrsen, B., & Vedel, J. 2007. Identification by facial recognition, gait analysis and photogrammetry: The Anna Lindh murder. In: Brickley, M., & Ferllini, R. (Eds.) *Forensic Anthropology: Case studies from Europe* pp. 232-244. Charles C. Thomas Publisher Ltd., Springfield, Illinois, U.S.A.

Micheletti, N., Chandler, J. H. & Lane, S. N. 2015. Structure from Motion (SfM) Photogrammetry. In: Clarke, L. E. & Nield, J. M. (Eds.) *Geomorphological Techniques* (Online Edition) Chap. 2, Sec. 2.2. British Society for Geomorphology, London, UK. http://www.geomorphology.org.uk/sites/default/files/geom_tech_chapters/2.2.2_sfm.pdf. Accessed 6.3.2016.

Micheletti, N., Chandler, J. H., & Lane, S. N. 2014. Investigating the geomorphological potential of freely available and accessible structure-from-motion photogrammetry using a smartphone. *Earth Surface Processes and Landforms*, 40(4): 473–486.

Oliensis, J. 2000. A Critique of Structure-from-Motion Algorithms. *Computer Vision and Image Understanding*, 80: 172–214.

Page, M., Taylor, J., & Blenkin, M. 2011. Forensic Identification Science Evidence Since Daubert: Part II – Judicial Reasoning in Decisions to Exclude Forensic Indentification on Grounds of Reliability. *Journal of Forensic Science*, 56(4): 913-917.

Paterson, A. & Franklin, D. The 1629 mass grave for Batavia victims, Beacon Island, Houtman Abrolhos Islands, Western Australia. *Australian Historical Archaeology*, 22: 71-78.

Plets, G., Gheyle, W., Verhoeven, G., De Reu, J., Bourgeois, J., Verhegge, J., & Stichelbaut, B. 2012. Three-dimensional recording of archaeological remains in the Altai Mountains. *ANTIQUITY*, 86: 884–897.

Pollefeys, M., Nister, D., Frahm, J.-M., Akbarzadeh, A., Mordohai, P., Clipp, B., Engels, C., Gallup, D., Kim, S.-J., Merrell, P., Salmi, C., Sinha, S., Talton, B., Wang, L., Yang, Q., Stewenius, H., Yang, R., Welch, G., & Towles, H. 2008. Detailed Real-Time Urban 3D Reconstruction From Video. *International Journal of Computer Vision*, 78(2): 143-167.

Remondino, F., Spera, M. G., Nocerino, E., Menna, F., & Nex, F. 2014. State of the Art in High Density Image Matching. *The Photogrammetric Record*, 29(146): 144–166.

Remondino, F., Del Pizzo, S., Kersten, T., & Troisi, S., 2012. Low-cost and open-source solutions for automated image orientation – A critical overview. In: Ioannides, M., Fritsch, D., Leissner, J., Davies, R., Remondino, F., & Caffo, R. (Eds.) *Progress in Cultural Heritage Preservation* pp. 40-54. EuroMed 2012, Lecture Notes in Computer Science, Vol. 7616.

Remondino, F., El-Hakim, S. F., Gruen, A. & Zhang, L. 2008. Turning images into 3-D models. IEEE Signal Process Magazine, 25(4): 55–65.

Robertson, G. 2000. Forensic Analysis of Imprint Marks on Skin Utilizing Digital Photogrammetric Techniques. In: Chikatsu, H. & Van den Heuvel, F. (Eds.) *International Archives of Photogrammetry and Remote Sensing*, Technical Commission V: Close-Range Techniques and Machine Vision, Vol. XXXIII(Part B5): 669-676. XIXth ISPRS Congress, 16.-23.7.2000, Amsterdam, The Netherlands.

http://www.isprs.org/proceedings/XXXIII/congress/part5/669_XXXIII-part5.pdf. Accessed 3.6.2016.

Rüther, H., Smit, J., & Donatius, K. 2012. Comparison of Close-Range Photogrammetry to Terrestrial Laser Scanning for Heritage Documentation. *South African Journal of Geomatics*, 1(2): 149-162.

Schrotter, G. 2009. *Full Body Modeling from Video Sequences.* Doctoral dissertation. http://e-collection.library.ethz.ch/eserv/eth:494/eth-494-02.pdf. Accessed 16.4.2016.

Seitsonen, O. & Holappa, M. 2011. Dokumentointi ruumishautakaivauksilla: Esimerkki Lappeenrannan Huhtiniemestä. In: Salo, K. & Niukkanen, M. (Eds.) *Arkeologisten hautakaivausten tutkimusmenetelmät* pp. 36-46. Museovirasto, Museoviraston rakennushistorian osaston raportteja 22. http://www.nba.fi/fi/File/1140/hautakaivausjulkaisu.pdf. Accessed 1.4.2016.

Shan, Q., Adams, R., Curless, B., Furukawa, Y., & Seitz, S. M. 2013. The visual turing test for scene reconstruction. *Proceedings of International Conference on 3D Vision (3DV '13):* 25-32. IEEE Computer Society, Washington DC, USA.

Shortis, M. R., Bellman, C. J., Robson, S., Johnston, G. J., & Johnson, G. W. 2006. Stability of zoom and fixed lenses used with digital SLR cameras. *International Archives Photogrammetry Remote Sensing and Spatial Information Sciences*, 36: 285-290. http://www.isprs.org/proceedings/XXXVI/part5/paper/SHOR_617.pdf. Accessed 6.3.2016.

Skinner, M., York, H. P. & Connor, M. A. 2002. Postburial Disturbance of Graves in Bosnia-Herzegovina. In: Haglund, W. D. & Sorg, M. H. (Eds.) *Advances in Forensic Taphonomy. Method, Theory, and Archaeological Perspectives* pp. 293-308. CRC Press, Boca Raton, Florida, U.S.A.

Snavely, N., Seitz, S. N., & Szeliski, R. 2008. Modeling the world from internet photo collections. *International Journal of Computer Vision* 80: 189-210.

Szeliski, R. 2010. *Computer Vision: Algorithms and Applications*. Springer, London, UK.

Thali, M. J., Braun, M., & Dirnhofer, R. 2003. Optical 3D surface digitizing in forensic medicine: 3D documentation of skin and bone injuries. *Forensic Science International*, 137: 203-208.

Thali, M. J., Braun, M., Brüschweiler, W., & Dirnhofer, R. 2000. Matching tire tracks on the head using forensic photogrammetry. *Forensic Science International*, 113: 281-287.

Tomasi, C., & Zhang, J. 1995. Is Structure-From-Motion Worth Pursuing? Seventh International Symposium on Robotics Research, Springer Verlag, 1995.

Tuller, H. & Durić, M. 2006. Keeping the pieces together: comparison of mass grave excavation methodology. *Forensic Science International,* 156(2-3): 192-200.

Ullman, S. 1979. The interpretation of structure from motion. *Proceedings of the Royal Society of London,* B 203: 405-426.

Urbanova, P., Hejna, P., & Mikoláš, J. 2015. Testing photogrammetry-based techniques for three-dimensional surface documentation in forensic pathology. *Forensic Science International*, 250: 77-86.

Verhoeven, G., Doneus, M., Briese, Ch., & Vermeulen, F. 2012. Mapping by matching: a computer vision-based approach to fast and accurate georeferencing of archaeological aerial photographs. *Journal of Archaeological Science,* 39: 2060-2070.

Westoby, M. J., Brassington, J., Glasser, N. F., Hambrey, M. J., & Reynolds, J. M. 2012. Structure-from-motion photogrammetry: A low-cost, effective tool for geoscience applications. *Geomorphology*, 179: 300-314.

*Manuals & Standards:*

Agisoft LCC. 2014. Agisoft PhotoScan User Manual: Professional Edition, Version 1.1. Available at: http://www.agisoft.com/pdf/photoscan-pro_1_1_en.pdf.

American Society for Photogrammetry and Remote Sensing (ASPRS). Website. http://www.asprs.org/a/society/about.html. Accessed 20.4.2016.

Association of Chief Police Officers (ACPO). ACPO Good Practice Guide for Digital Evidence, March 2012. Available at: http://www.digital-detective.net/digital-forensics-documents/ACPO_Good_Practice_Guide_for_Digital_Evidence_v5.pdf.

Cornell University Law School, Legal Information Institute. Federal Rules of Evidence, Rule 702 Testimony by Expert Witnesses, as amended to December 1, 2015. https://www.law.cornell.edu/rules/fre/rule_702. Accessed 23.3.2016.

Cornell University Law School, Legal Information Institute. Federal Rules of Evidence, Rule 901 Authenticating or Identifying Evidence, as amended to December 1, 2015. https://www.law.cornell.edu/rules/fre/rule_901. Accessed 2.4.2016.

Cornell University Law School, Legal Information Institute. Federal Rules of Evidence, Rule 1001 Definitions That Apply to This Article, as amended to December 1, 2015. https://www.law.cornell.edu/rules/fre/rule_1001. Accessed 30.3.2016.

Forensic Science Regulator. 2014. Forensic science providers: codes of practice and conduct, 2016. https://www.gov.uk/government/publications/forensic-science-providers-codes-of-practice-and-conduct-2016. Accessed 2.4.2016.

Scientific Working Group on Digital Evidence. 2015. https://www.swgde.org/. Accessed 11.4.2016.

Scientific Working Group on Digital Evidence. Guidelines for the Forensic Imaging Practitioner, Section 1: Overview of SWGIT and the Use of Imaging Technology in the Criminal Justice System, Version 3.3 2010.06.11. https://www.swgit.org/pdf/Section%201%20Overview%20of%20SWGIT%20and%20the%20Use%20of%20Imaging%20Technology%20in%20the%20Criminal%20Justice%20System?docID=35. Accessed 31.3.2016.

Scientific Working Group Imaging Technology (SWGIT). Guidelines for the Forensic Imaging Practitioner, Section 5: Guidelines for Image Processing, Version 2.1 2010.01.15. https://www.swgit.org/pdf/Section%205%20Guidelines%20for%20Image%20Processing?docID=49. Accessed 29.3.2016.

Scientific Working Group Imaging Technology (SWGIT). Guidelines for the Forensic Imaging Practitioner, Section 11: Best Practices for Documenting Image Enhancement, Version 1.3 2010.01.15. https://www.swgit.org/pdf/Section%2011%20Best%20Practices%20for%20Documenting%20Image%20Enhancement?docID=37. Accessed 21.3.2016.

Scientific Working Group on Digital Evidence. Guidelines for the Forensic Imaging Practitioner, Section 13: Best Practices for Maintaining the Integrity of Digital Images and Digital Video, Version 1.1 2012.01.13. https://www.swgit.org/pdf/Section%2013%20Best%20Practices%20for%20Maintaining%20the%20Integrity%20of%20Digital%20Images%20and%20Digital%20Video?docID=54. Accessed 31.3.2016.

Scientific Working Group on Digital Evidence. Guidelines for the Forensic Imaging Practitioner, Section 15: Best Practices for Archiving Digital and Multimedia Evidence (DME) in the Criminal Justice System, Version 1.1 2012.01.13. https://www.swgit.org/pdf/Section%2015%20Best%20Practices%20for%20Archiving%20Digital%20and%20Multimedia%20Evidence%20(DME)%20in%20the%20Criminal%20Justice%20System?docID=55. Accessed 31.3.2016.

Scientific Working Group Imaging Technology (SWGIT). Guidelines for the Forensic Imaging Practitioner, Section 18: Best Practices for Automated Image Processing, Version 1.0 2010.01.15. https://www.swgit.org/pdf/Section%2018%20Best%20Practices%20for%20Automated%20Image%20Processing?docID=41. Accessed 30.3.2016.

Scientific Working Group Imaging Technology (SWGIT). Documents. Available at: https://www.swgit.org/documents/Current%20Documents.

Scientific Working Group on Digital Evidence. SWGDE Best Practices for the Forensic Use of Photogrammetry, Version: 1.0 (September 29, 2015). https://www.swgde.org/documents/Current%20Documents/2015-09-29%20SWGDE%20Best%20Practices%20for%20the%20Forensic%20Use%20of%20Photogrammetry. Accessed 27.3.2014.

United Nations. 1991. *United Nations Manual on the Effective Prevention and Investigation of Extra-legal, Arbitrary and Summary Executions.* U.N. Doc. E/ST/CSDHA/.12 (1991). https://www1.umn.edu/humanrts/instree/executioninvestigation-91.html. Accessed 2.4.2016.

*Court Cases:*

*Canal Authority of Florida v. Callaway*, 489 F.2d 567, 571 (5th Cir., 1974). https://casetext.com/case/canal-authority-of-state-of-fla-v-callaway. Accessed 24.3.2016.

*Clark v. Cantrell*, 339 S.C. 369, 384, 529 S.E.2d 528 (2000). http://caselaw.findlaw.com/sc-supreme-court/1481182.html. Accessed 29.3.2016.

*Daubert v. Merrell Dow Pharmaceuticals, Inc*. 509 U. S. 579, 113 S.Ct. 2786, 125 L.Ed.2d 469 (1993). https://supreme.justia.com/cases/federal/us/509/579/case.pdf. Accessed 22.3.2016.

*Goodman vs. Crystal River*, 669 F.Supp. 394, 396 (M.D. FL, 1987). https://casetext.com/case/goodman-v-city-of-crystal-river. Accessed 24.3.2016.

*Government of the Virgin Islands v. Austin Jacobs*, 53 Fed.Appx. 651 C.A.3 (Virgin Islands, 2002) (Unreported).

*Heatherly vs. Alexander*, 421 F.3d 638, 645 (8th Cir. 2005). https://casetext.com/case/heatherly-v-alexander. Accessed 24.3.2016.

*Kannankeril v. Terminix Int'l, Inc*., 128 F.3d 802, 809 (3d Cir. 1997).

*Missouri vs. Department of Army Corp. of Engineers*, 526 F.Supp 660, 672 (W.D. MO, 1980). https://casetext.com/case/state-of-mo-ex-rel-ashcroft-v-dept-of-army. Accessed 24.3.2016.

*Napeahi vs. Wilson*, 1996 U.S. 18 (D.C. HI, 1996). https://casetext.com/case/napeahi-v-wilson. Accessed 24.3.2016.

*Papadolous v. Fred Meyers Stores, Inc.* W.D.Wash. 11-22-2006. https://casetext.com/case/papadopoulos-v-fred-meyer-stores. Accessed 28.3.2016.

*Ramirez v. State*, 819 So.2d 836 (Fla., 2001). http://caselaw.findlaw.com/fl-supreme-court/1488958.html. Accessed 29.3.2016.

*State of New Hampshire v. Richard Langill*, No. 2007-300 (Sup. Ct. Rockingham 13 Feb 2008) (Unreported). http://www.clpex.com/Information/NHvLANGILL/NH_Supreme_Court_Decision-4Apr08.pdf. Accessed 30.3.2016.

*State v. Swinton*, 2004. https://www.jud.ct.gov/external/supapp/Cases/AROcr/CR268/268cr60.pdf. Accessed 29.3.2016.

*United States v. Green,* 405 F.Supp.2d 104 (D.Mass., 2005). http://www.nlada.org/forensics/for_lib/Documents/1143832772.0/US%20vs.%20Green.pdf. Accessed 28.3.2016.

*United States v. Kyler*, 11th Cir. 2011. http://law.justia.com/cases/federal/appellate-courts/ca11/10-11318/201011318-2011-06-02.html. Accessed 24.3.2016.

*United States v. Monteiro,* 407 F.Supp.2d 351 (D.Mass., 2006). https://casetext.com/case/us-v-monteiro-10. Accessed 29.3.2016.

*United States v. Saelee,* 162 F.Supp.2d 1097 (D.Alaska 2001). http://law.justia.com/cases/federal/district-courts/FSupp2/162/1097/2319759/. Accessed 29.3.2016.

*United States v. Sullivan,* 246 F.Supp.2d 702, 703 (E.D.Ky. 2003). http://law.justia.com/cases/federal/district-courts/FSupp2/246/700/2435106/. Accessed 28.3.2016.

*United States v. Quinn*, 18 F.3d 1461 (9th Cir. 1994). https://casetext.com/case/us-v-quinn-16#p1464. Accessed 26.3.2016.

*United States v. Williams*, 3rd Cir. 2007. http://caselaw.findlaw.com/us-3rd-circuit/1010845.html. Accessed 24.3.2016.

*Waste Management of Alameda County, Inc. v. East Bay Regional Park District*, 135 F.Supp.2d 1071, 1081 (N.D. CA. 2001). http://law.justia.com/cases/federal/district-courts/FSupp2/135/1071/2503380/. Accessed 24.3.2016.

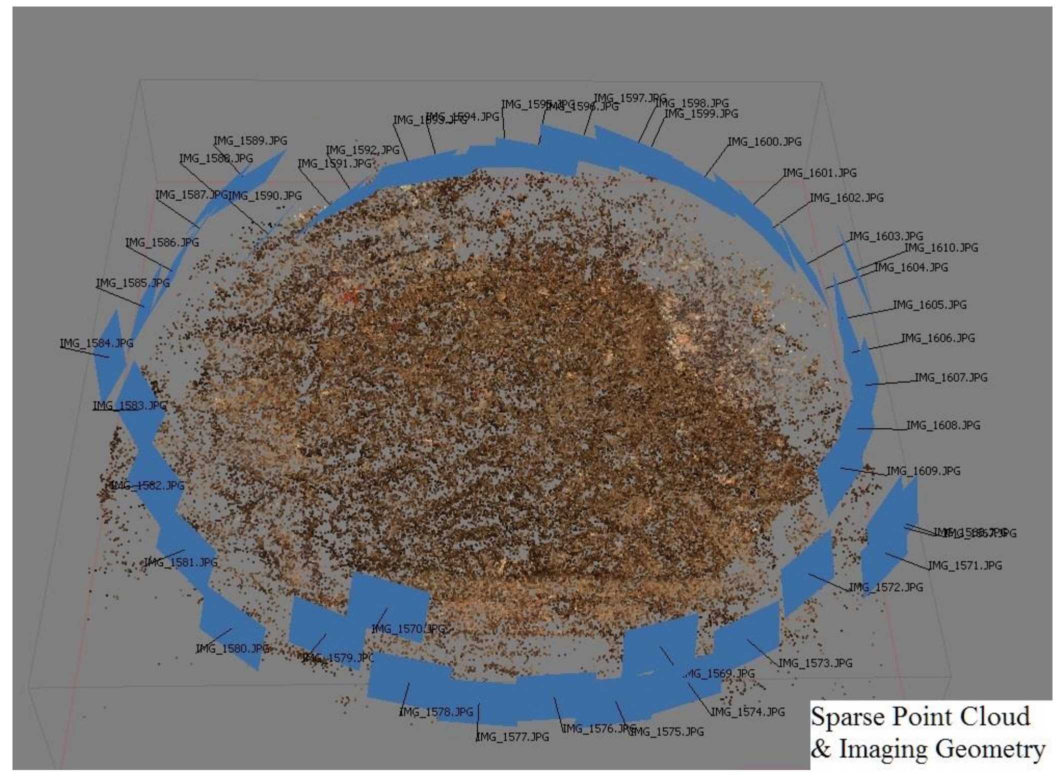
**Appendix 1: Results of Photogrammetric Image Processing**

**I Table of Photogrammetric Image Processing Results**

| | | **Layer 0** | **Layer 1** | **Layer 2** | **Layer 3** | **Layer 4** | **Layer 5** | **Layer 6** | **Layer 7** |
|---|---|---|---|---|---|---|---|---|---|
| | Images as input | 44 | 65 | 80 | 76 | 77 | 80 | 75 | 57 |
| Image alignment | settings | high accuracy; generic pair preselection; key point limit of 40,000; mask not used | high accuracy; generic pair preselection; key point limit of 40,000; mask not used | high accuracy; generic pair preselection; key point limit of 40,000; mask not used | high accuracy; generic pair preselection; key point limit of 40,000; mask not used | high accuracy; generic pair preselection; key point limit of 40,000; features contrained by mask | high accuracy; generic pair preselection; key point limit of 40,000; features contrained by mask | high accuracy; generic pair preselection; key point limit of 40,000; mask not used | high accuracy; generic pair preselection; key point limit of 40,000; mask not used |
| | points | 134,816 | 189,400 | 318,677 | 252,355 | 313,614 | 342,002 | 369,794 | 221,453 |
| | reprojection error | 0.316882 (0.973773 max) | 0.432386 (1.32928 max) | 0.376794 (1.18617 max) | 0.355426 (1.07287 max) | 0.355426 (1.07287 max) | 0.40035 (1.2109 max) | 0.40932 (1.24243 max) | 0.318014 (0.981449 max) |
| | effective overlap | 2.5999 | 2.92741 | 3.5702 | 3.33242 | 2.89524 | 3.25742 | 3.12456 | 3.73738 |
| | processing time | 2 min 13 s | 4 min 32 s | 9 min 30 s | 7 min 47 s | 6 min 36 s | 8 min 50 s | 8 min 46 s | 6 min 1 s |
| Dense point cloud generation | settings | ultra high quality; moderate depth filtering | ultra high quality; moderate depth filtering | ultra high quality; moderate depth filtering | ultra high quality; moderate depth filtering | high quality; moderate depth filtering | high quality; moderate depth filtering | high quality; moderate depth filtering | high quality; moderate depth filtering |
| | points | 31,604,505 | 29,475,419 | 28,620,476 | 27,784,226 | 12,147,843 | 13,194,342 | 14,489,981 | 4,890,287 |
| | processing time | 43 min 41 s | 1 h 39 min | 1 h 17 min | 1 h 16 min | 4 min 50 s | 6 min 1 s | 5 min 20 s | 6 min 12 s |
| Mesh generation | settings | arbitrary sourface type; dense point cloud as source data; disabled interpolation | arbitrary sourface type; dense point cloud as source data; disabled interpolation | arbitrary sourface type; dense point cloud as source data; disabled interpolation | arbitrary sourface type; dense point cloud as source data; disabled interpolation | arbitrary sourface type; dense point cloud as source data; disabled interpolation | arbitrary sourface type; dense point cloud as source data; disabled interpolation | arbitrary sourface type; dense point cloud as source data; disabled interpolation | arbitrary sourface type; dense point cloud as source data; disabled interpolation |
| | faces | 6,320,891 | 5,848,049 | 5,724,094 | 5,447,180 | 2,439,114 | 2,650,360 | 2,907,022 | 924,857 |
| | vertices | 4,833,220 | 3,926,026 | 3,334,406 | 3,400,688 | 1,560,670 | 1,771,045 | 1,974,518 | 483,164 |
| | processing time | 20 min 53 s | 11 min 52 s | 8 min 38 s | 10 min 44 s | 5 min 28 s | 7 min 50 s | 7 min 58 s | 1 min 13 s |
| Texture mapping | settings | adaptive orthophoto mapping mode; mosaic blending mode | adaptive orthophoto mapping mode; mosaic blending mode | adaptive orthophoto mapping mode; mosaic blending mode | adaptive orthophoto mapping mode; mosaic blending mode | adaptive orthophoto mapping mode; mosaic blending mode | adaptive orthophoto mapping mode; mosaic blending mode | adaptive orthophoto mapping mode; mosaic blending mode | adaptive orthophoto mapping mode; mosaic blending mode |
| | texture size | 4,096 X 4,096 | 4,096 X 4,096 | 4,096 X 4,096 | 4,096 X 4,096 | 4,096 X 4,096 | 4,096 X 4,096 | 4,096 X 4,096 | 4,096 X 4,096 |
| | processing time | 4 min 58 s | 5 min 22 s | 4 min 19 s | 4 min 7 s | 1 min 37 s | 2 min 51 s | 3 min 33 s | 41 s |

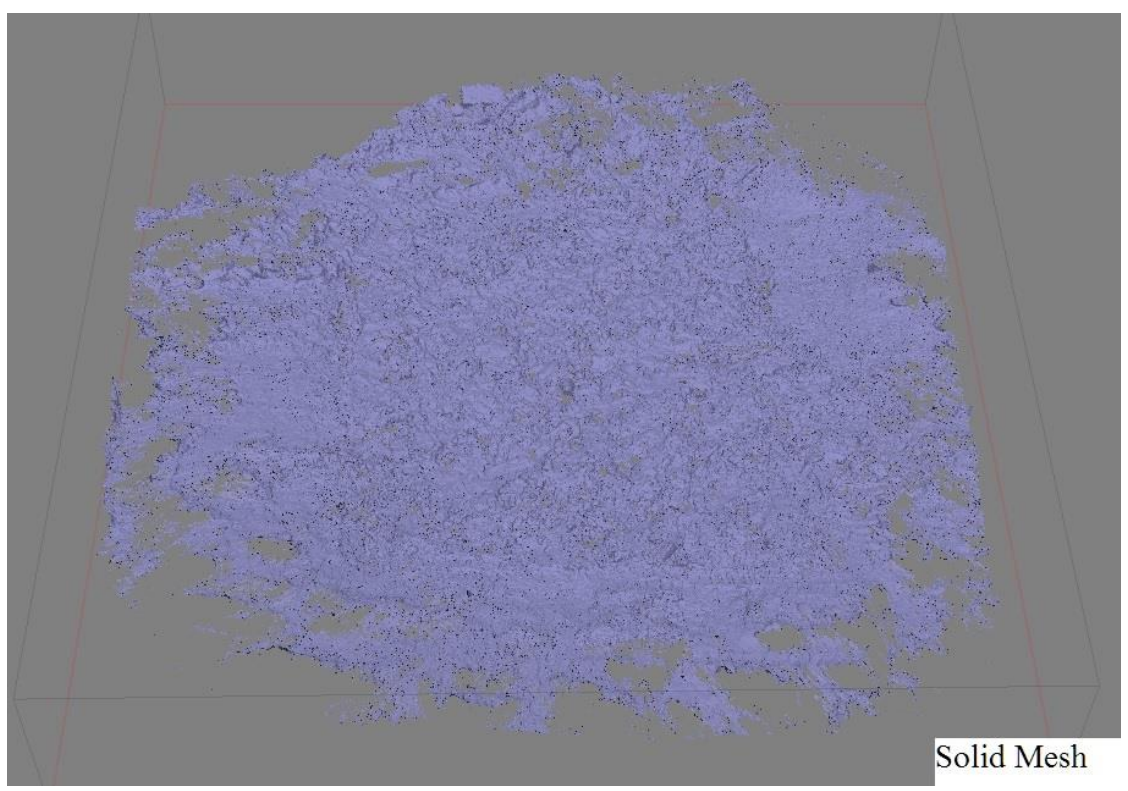
**II Photogrammetric Outputs of Image Processing**

**Layer 0: Ground disturbance consistent with a grave. Tire marks were clearly visible in the ground over and around the simulation mass grave.**



Sparse Point Cloud & Imaging Geometry

Dense Point Cloud

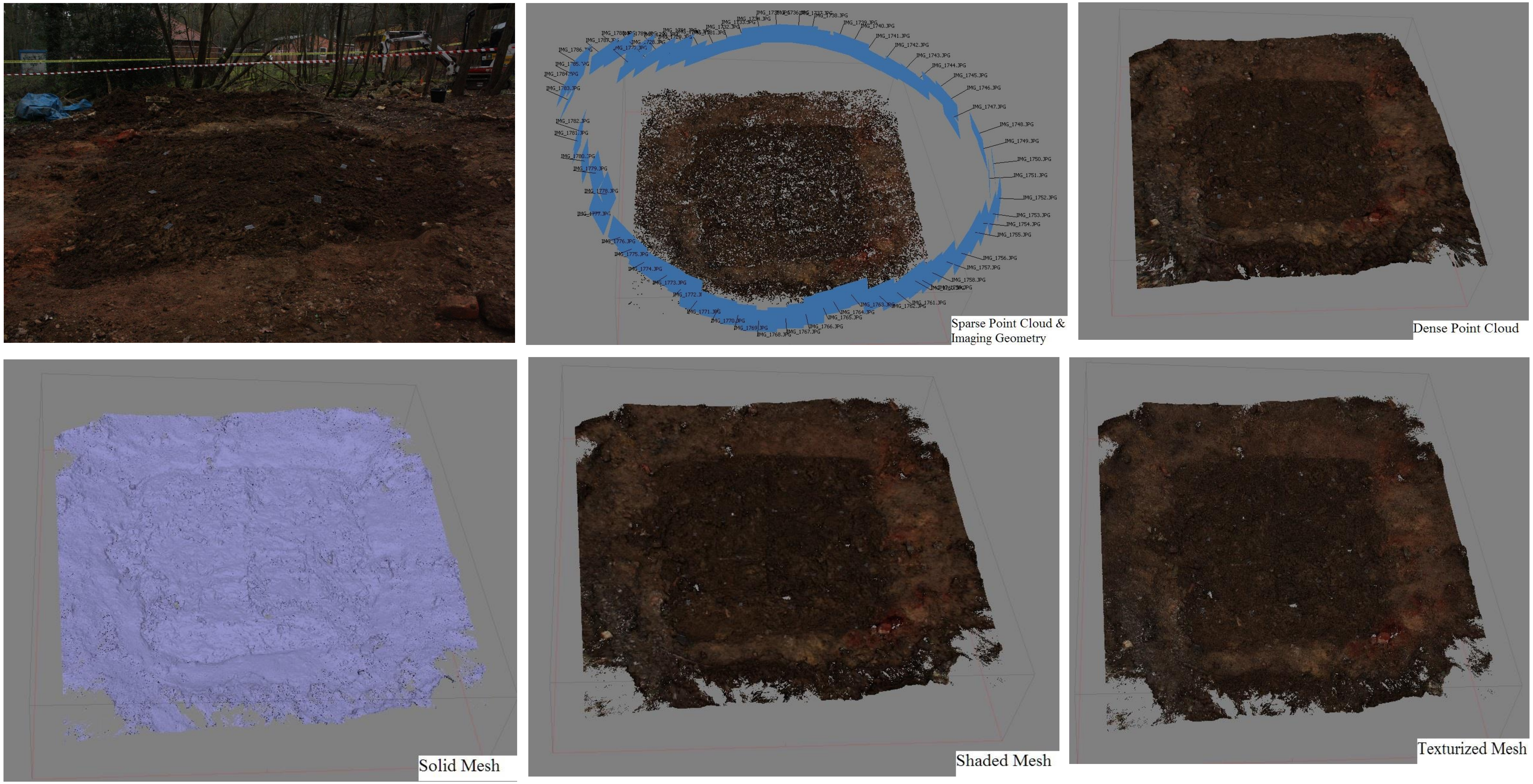


Solid Mesh

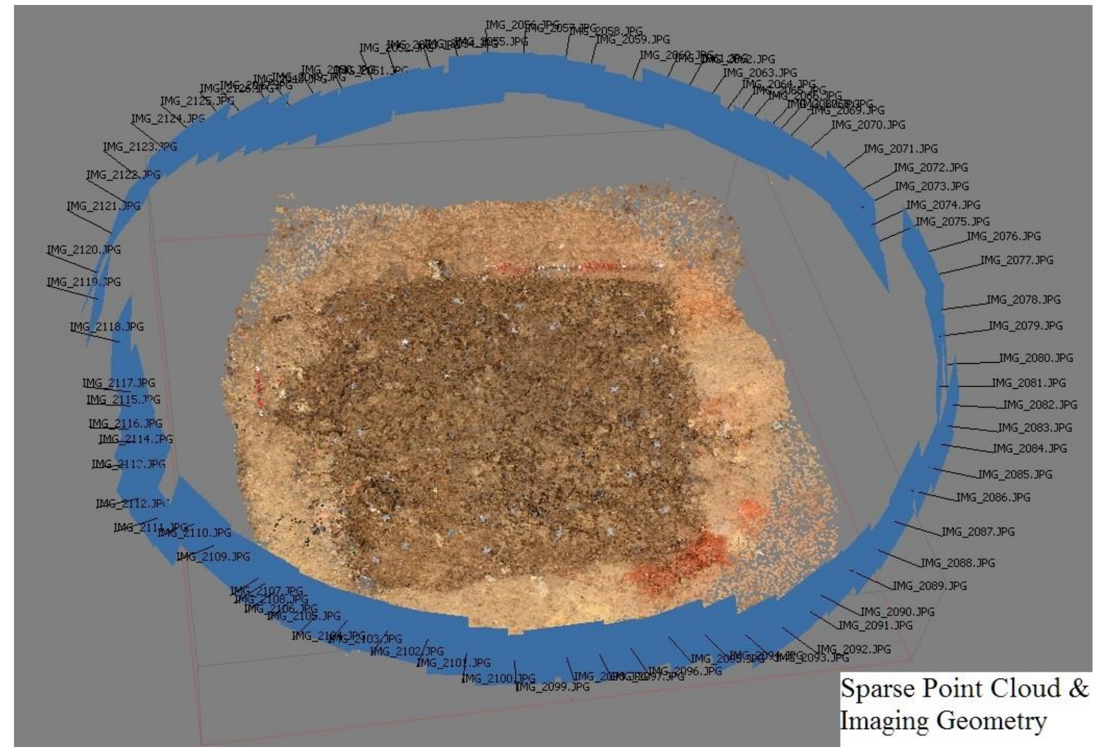
Shaded Mesh

Texturized Mesh

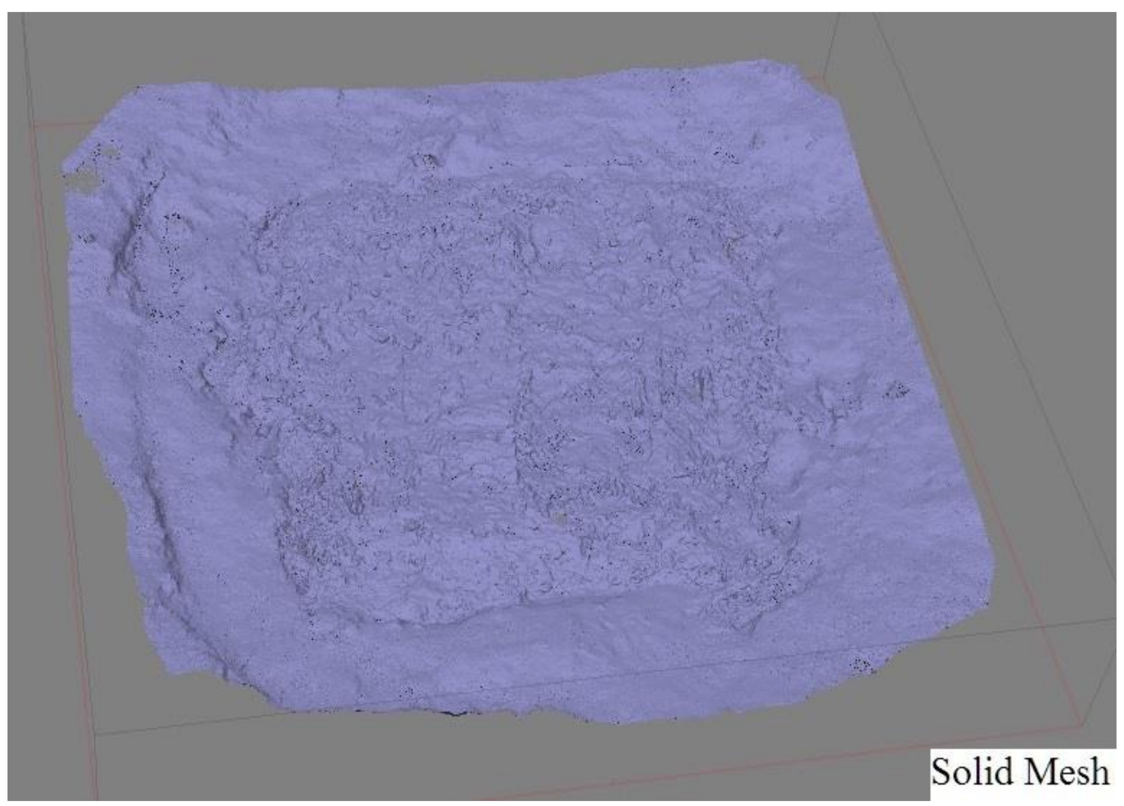
**Layer 1: The simulation mass grave after removing topsoil. The grave cut is not well defined.**



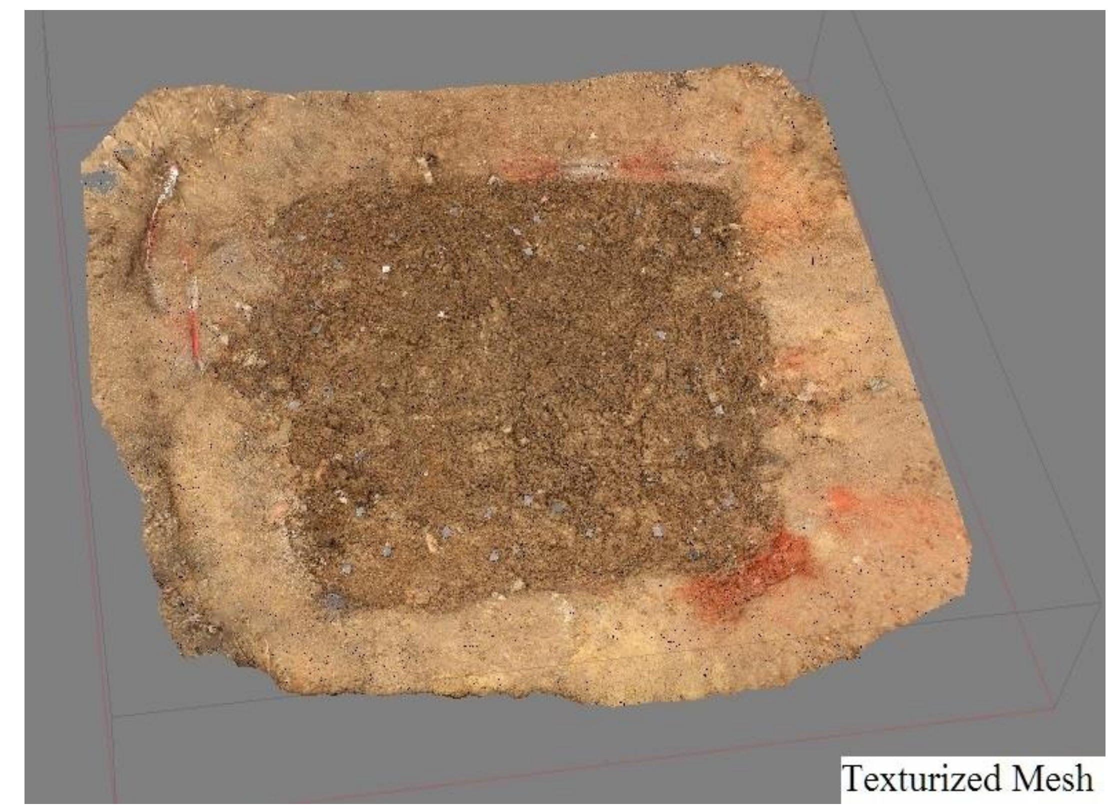
**Layer 2: The simulation mass grave after clearing the surroundings and defining the grave cut.**



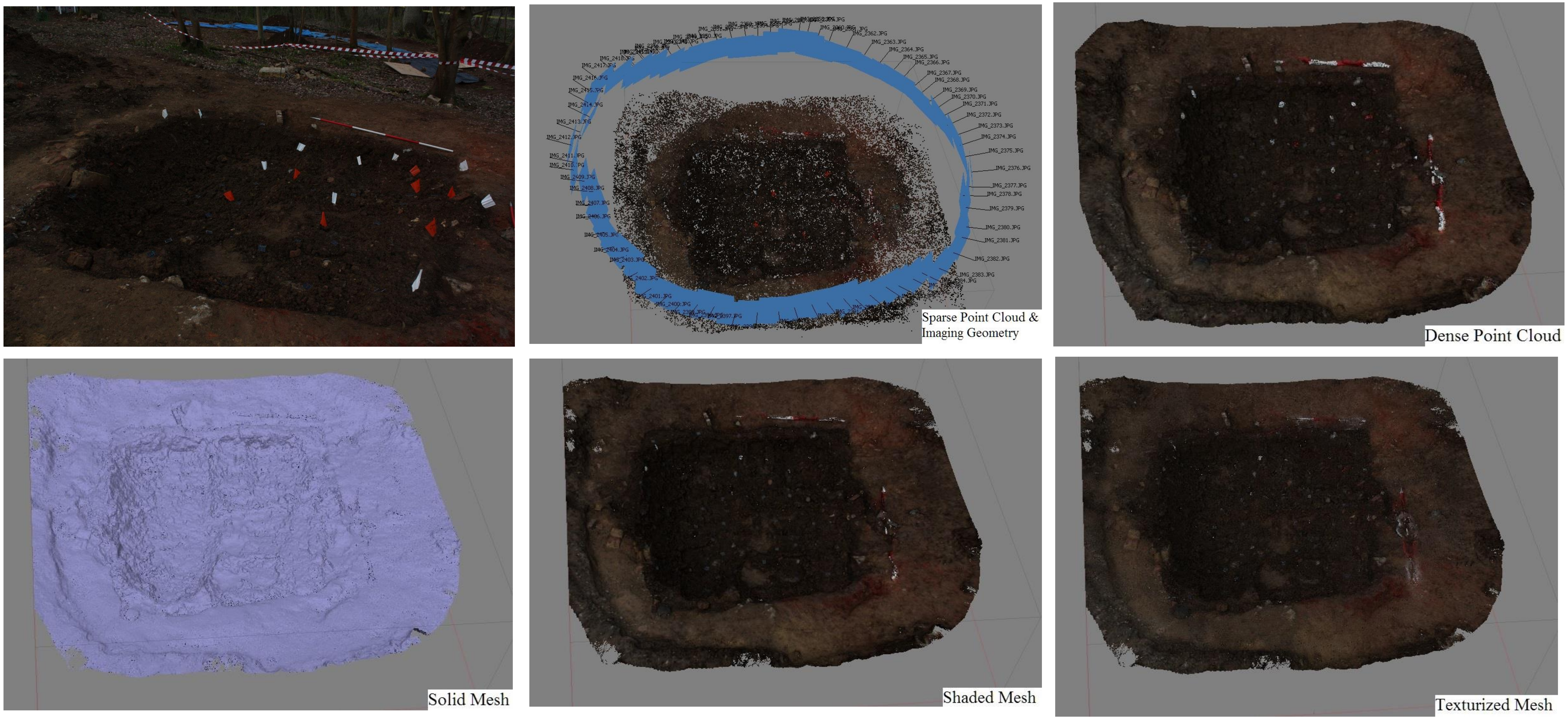




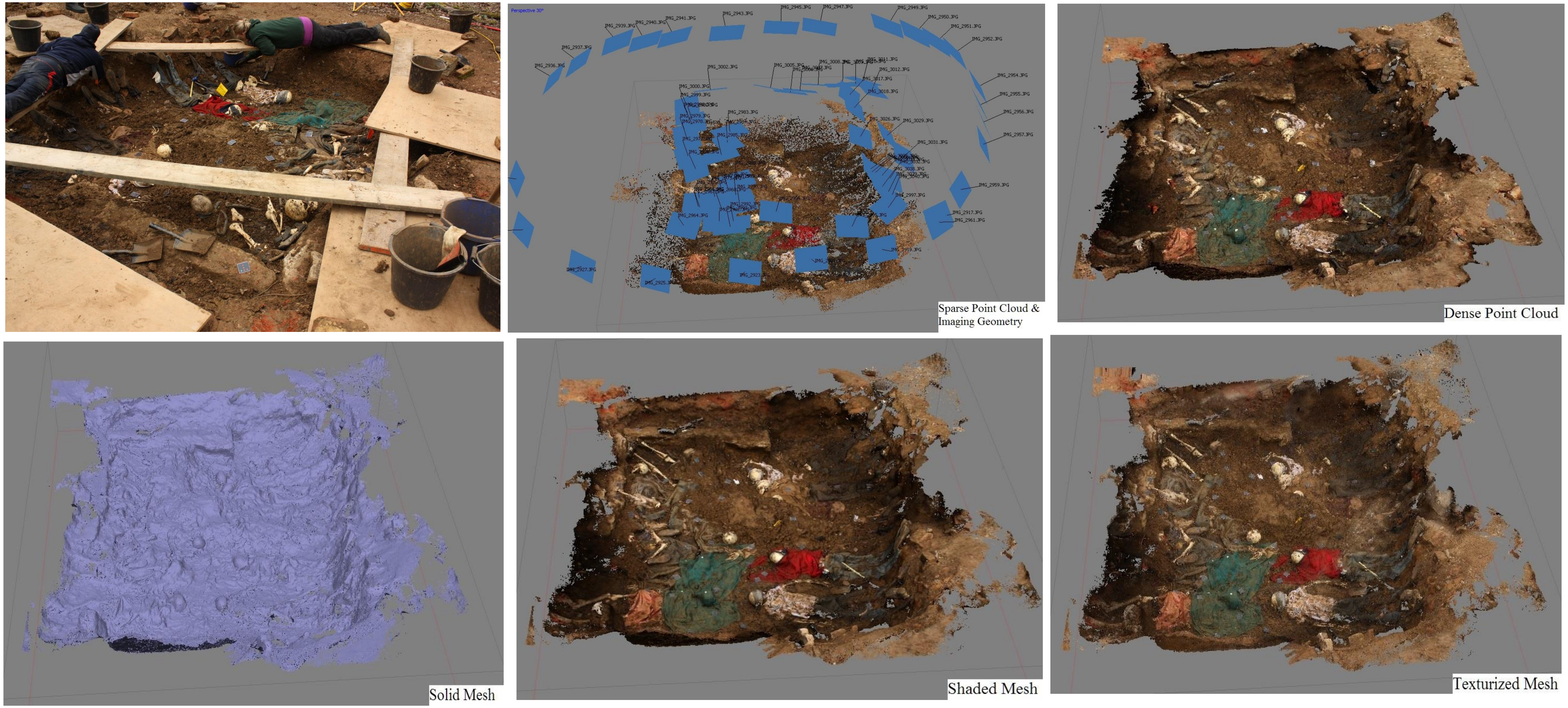




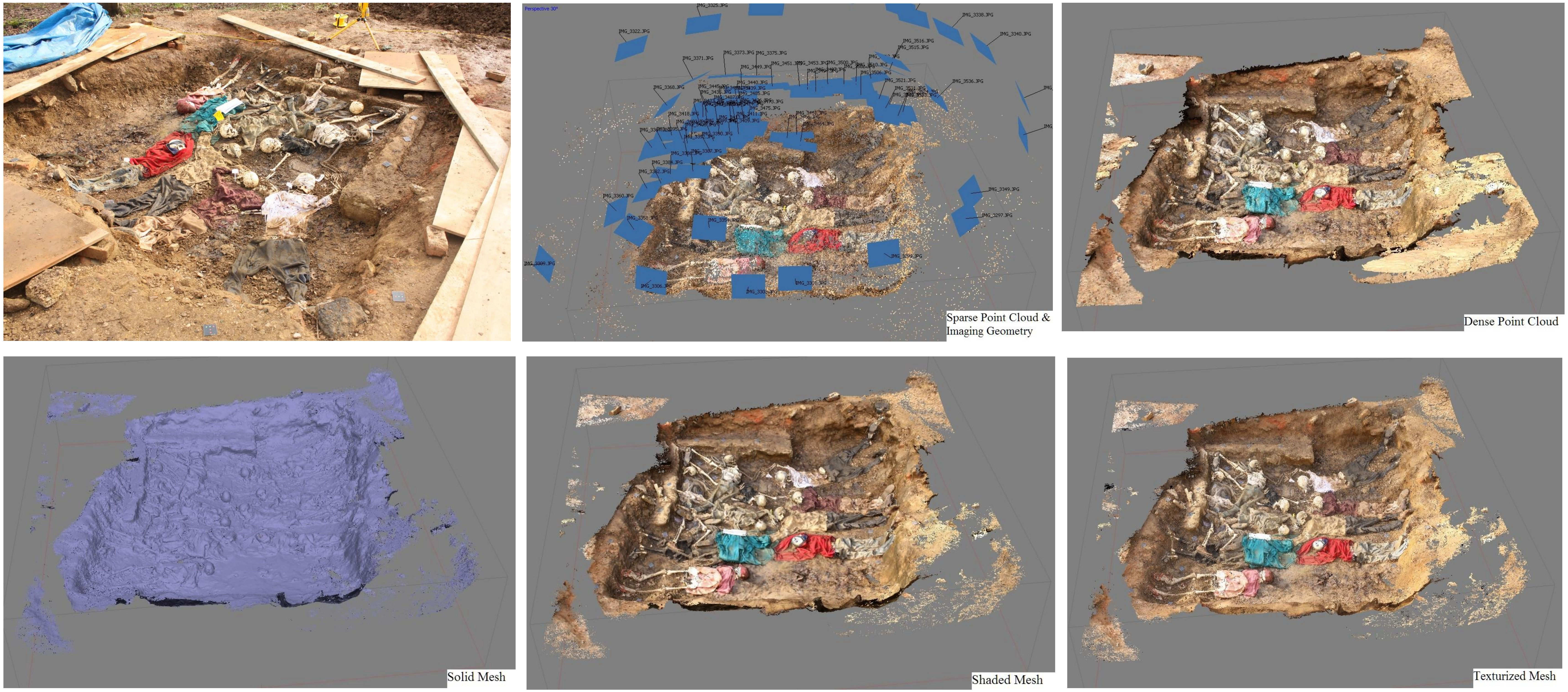
**Layer 3: The simulation mass grave after exposing the first pieces of evidence. Images had to be taken in decreasing daylight.**



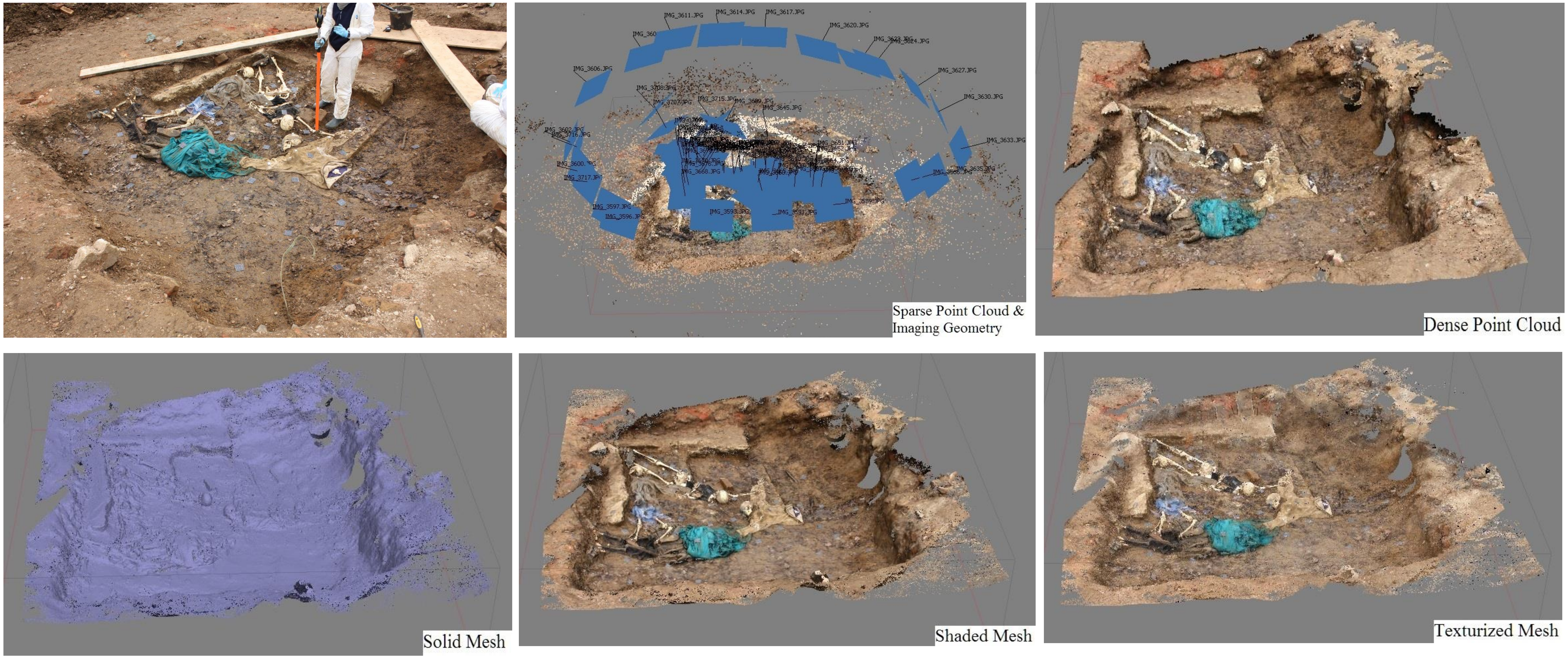
**Layer 4: The simulation mass grave after exposing the first individuals within the grave. Images had to be taken during an ongoing excavation.**



**Layer 5: The simulation mass grave after fully exposing the individuals within the grave. One individual was removed (the dark area on the lower left corner of the grave) before it could be documented for photogrammetric image processing.**



**Layer 6: The simulation mass grave after recovering six individuals. Images had to be taken during total station survey.**



**Layer 7: The simulation mass grave after recovering the remaining individuals and cleaning the grave floor. Images had to be taken in direct sunlight.**

# Appendix 2: Image Processing Report for Layer 5

**Agisoft's PhotoScan (Professional edition, version 1.1.6)**

**13 April 2016**

# Survey Data

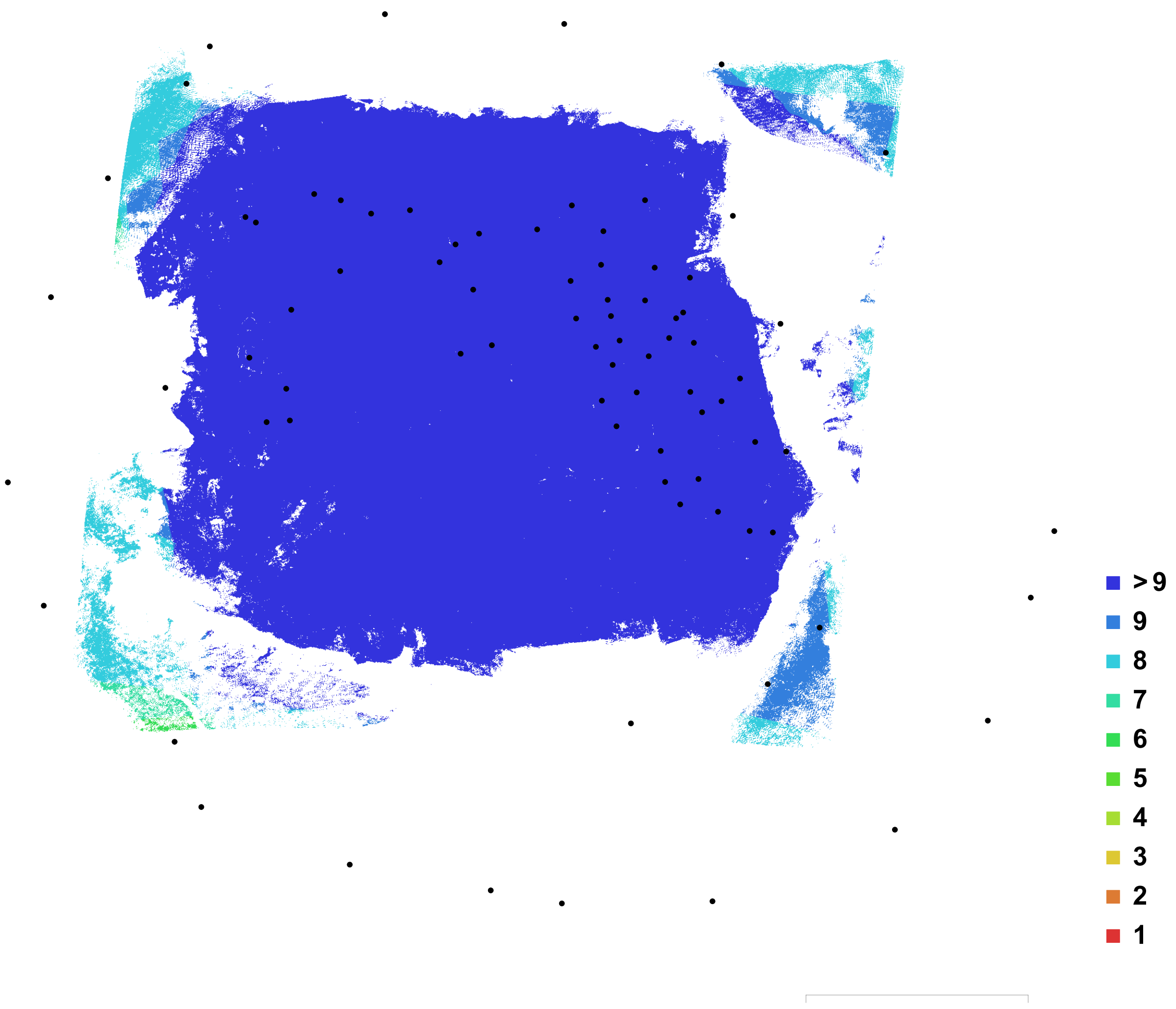



Fig. 1. Camera locations and image overlap.

| | | | |
|---|---|---|---|
| Number of images: | 80 | Camera stations: | 80 |
| Flying altitude: | 15.3 m | Tie points: | 342,002 |
| Ground resolution: | 4.83 mm/pix | Projections: | 988,989 |
| Coverage area: | 677 sq m | Reprojection error: | 0.4 pix |

| Camera Model | Resolution | Focal Length | Pixel Size | Precalibrated |
|---|---|---|---|---|
| Canon EOS 450D (18 mm) | 3088 x 2056 | 18 mm | 7.22 x 7.22 um | No |

Table 1. Cameras.

# Camera Calibration

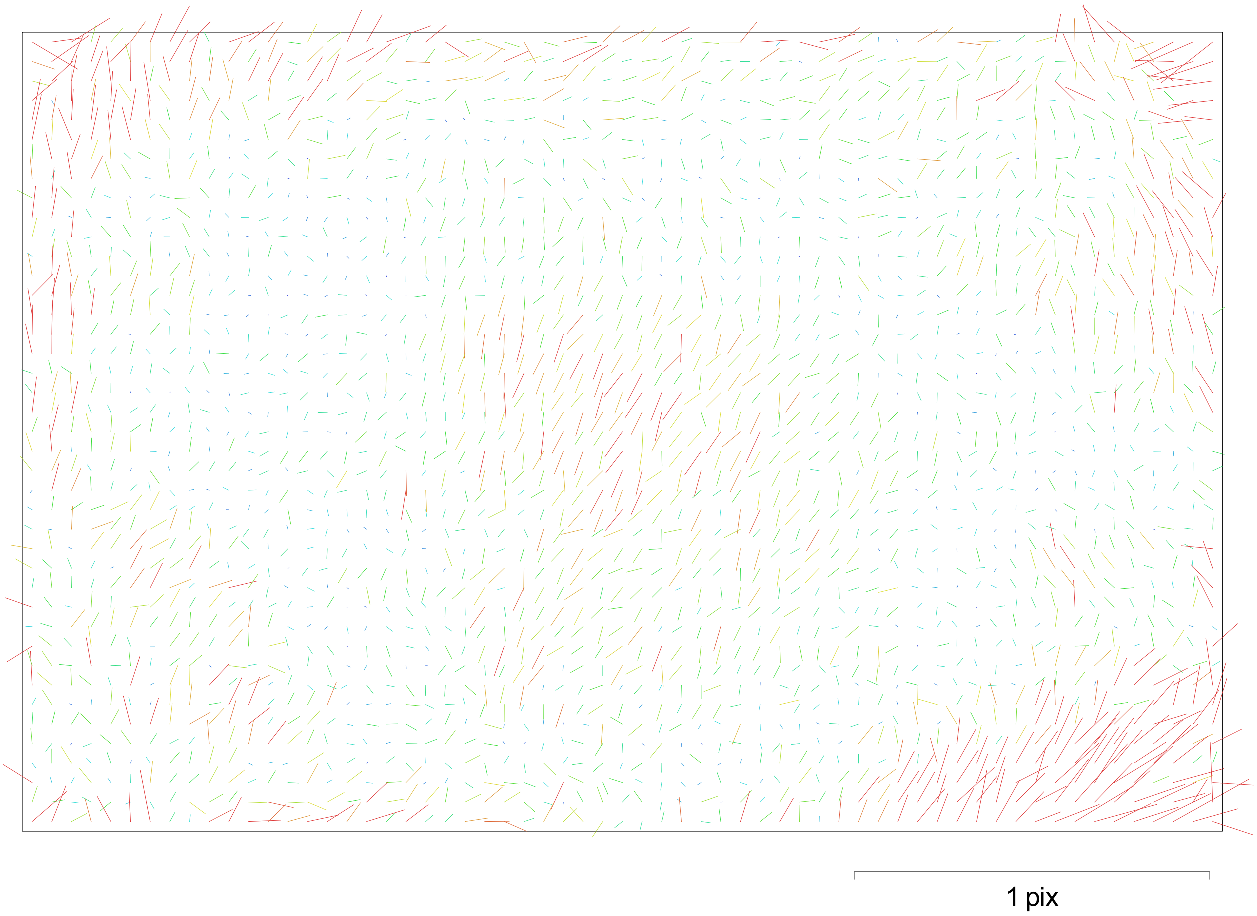



Fig. 2. Image residuals for Canon EOS 450D (18 mm).

**Canon EOS 450D (18 mm)**
80 images

| Resolution | Focal Length | Pixel Size | Precalibrated |
|---|---|---|---|
| **3088 x 2056** | **18 mm** | **7.22 x 7.22 um** | **No** |

| | | | |
|---|---|---|---|
| Type: | Frame | Skew: | 0 |
| Fx: | 2612.99 | Cx: | 1560.8 |
| Fy: | 2612.99 | Cy: | 1023.32 |
| K1: | -0.173726 | P1: | 0 |
| K2: | 0.173814 | P2: | 0 |
| K3: | -0.0301902 | P3: | 0 |
| K4: | 0 | P4: | 0 |

# Digital Elevation Model

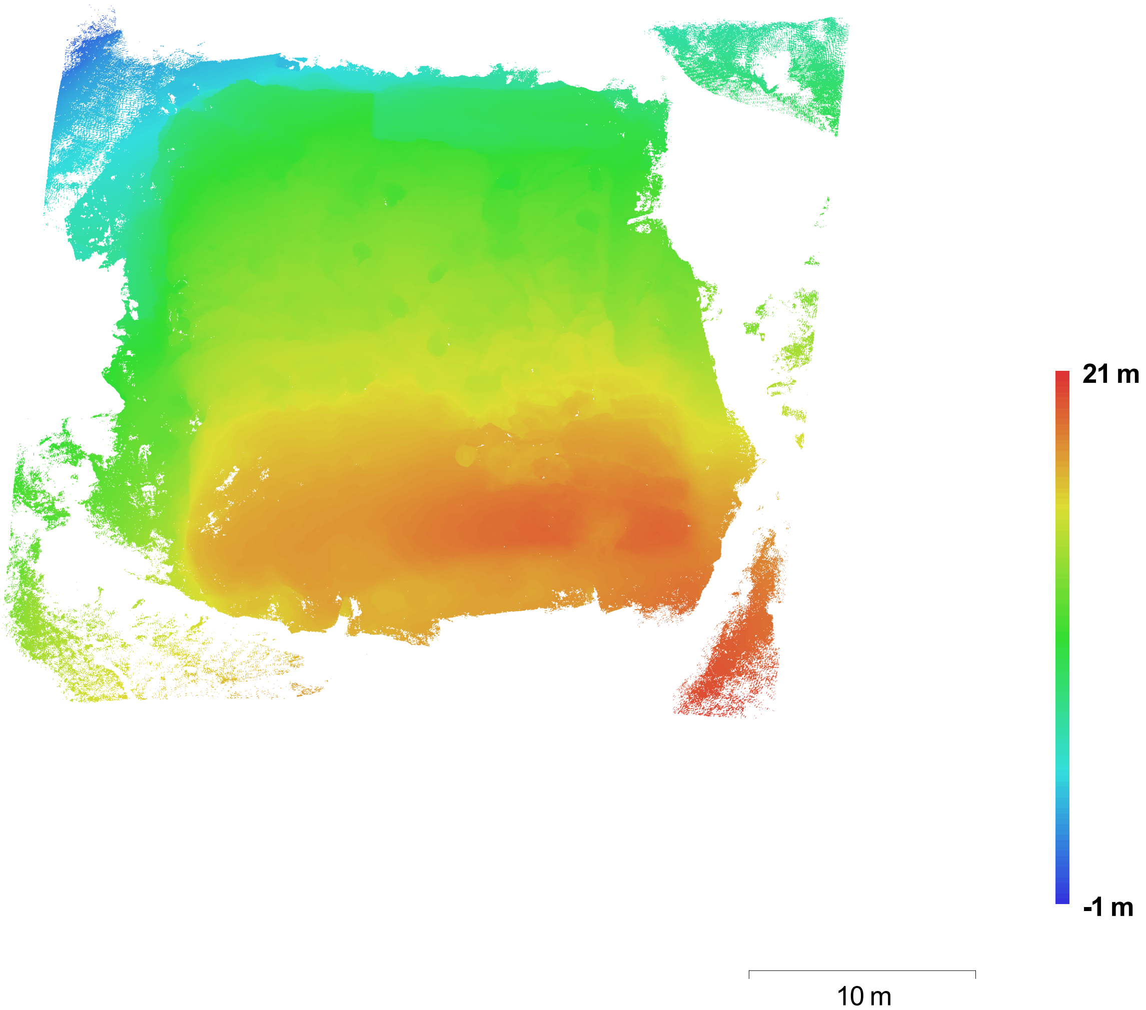



Fig. 3. Reconstructed digital elevation model.

| | |
|---|---|
| Resolution: | 9.66 mm/pix |
| Point density: | 10715.2 points per sq m |

# Processing Parameters

| | |
|---|---|
| **General** | |
| Cameras | 80 |
| Aligned cameras | 80 |
| Coordinate system | Local Coordinates |
| **Point Cloud** | |
| Points | 342,002 of 396,796 |
| Reprojection error | 0.40035 (1.2109 max) |
| Effective overlap | 3.25742 |
| **Alignment parameters** | |
| Accuracy | High |
| Pair preselection | Generic |
| Key point limit | 40,000 |
| Constrain features by mask | Yes |
| Matching time | 7 minutes 34 seconds |
| Alignment time | 1 minutes 16 seconds |
| **Dense Point Cloud** | |
| Points | 13,194,342 |
| **Reconstruction parameters** | |
| Quality | High |
| Depth filtering | Moderate |
| Processing time | 6 minutes 1 seconds |
| **Model** | |
| Faces | 2,650,360 |
| Vertices | 1,771,045 |
| Texture | 4,096 x 4,096, uint8 |
| **Reconstruction parameters** | |
| Surface type | Arbitrary |
| Source data | Dense |
| Interpolation | Disabled |
| Quality | High |
| Depth filtering | Moderate |
| Face count | 2,650,361 |
| Processing time | 7 minutes 50 seconds |
| **Texturing parameters** | |
| Mapping mode | Adaptive orthophoto |
| Blending mode | Mosaic |
| Texture size | 4,096 x 4,096 |
| UV mapping time | 1 minutes 36 seconds |
| Blending time | 1 minutes 15 seconds |